WAPD-TM-1297
DOE RESEARCH AND
DEVELOPMENT REPORT

BRAZING OF AM-350 STAINLESS STEEL LWBR FUEL ROD SUPPORT GRIDS

(LWBR Development Program)

FEBRUARY 1979

CONTRACT EY-76-C-11-0014

MASTER

BETTIS ATOMIC POWER LABORATORY
WEST MIFFLIN, PENNSYLVANIA

Operated for the U. S. Department of Energy by
WESTINGHOUSE ELECTRIC CORPORATION

DISCLAIMER

WAPD-TM-1297

BRAZING OF AM-350 STAINLESS STEEL
LWBR FUEL ROD SUPPORT GRIDS
(LWBR DEVELOPMENT PROGRAM)

L. P. Ebejer

February, 1979

Contract No. EY-76-C-11-0014

Printed in the United States of America
Available from the
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

BETTIS ATOMIC POWER LABORATORY PITTSBURGH, PENNSYLVANIA

Operated for the U. S. Energy Research and Development Administration by
WESTINGHOUSE ELECTRIC CORPORATION

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 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 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 is expected to be operated for about 3 to 4 years. At the end of this period, the core will be removed and the spent fuel shipped to the Naval Reactors Expended Core Facility for a 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 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 program will explore some of the problems that would be faced by industry in adapting technology confirmed in the LWBR program. Information to be 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 administered by the Division of Naval Reactors with the goal of developing practical improvements in the utilization of nuclear fuel resources for generation of electrical energy using water-cooled nuclear reactors.

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.

TABLE OF CONTENTS

					Page
I.	INTRODUCTION				1
II.	MATERIALS, EQUIPMENT AND PROCEDURES				5
	A.	Materials			5
		1.	AM-350 Precipitation - Hardening Stainless Steel Made from Air-Melted, Consumable Electrode Vacuum Remelted Ingots		5
			a.	Sheet Metal Components	6
			b.	Machined Bar Components	6
			c.	Wire Components	6
		2.	Brazing Filler Metal		7
			a.	Raw Materials	8
			b.	Process	8
		3.	Braze Alloy Binder		8
		4.	Stop-Off		8
		5.	Stop-Off Cement		9
	B.	Brazing Equipment			9
		1.	Fixturing		9
		2.	Brazing Furnace		10
	C.	Procedure			13
		1.	Component Cleaning		13
		2.	Stop-Off Application		14
		3.	Assembly and Braze Alloy Paste Application		15
		4.	Fixturing of Alloyed Grids		17
		5.	Brazing		18
			a.	Furnace Loading and Pumpdown	18
			b.	Thermal Cycle	19

				Page
III.	RESULTS			21
	A.	Visual Examination of Brazed Joints		21
	B.	Metallographic Properties		23
		1.	Microstructure	23
		2.	Preproduction Grids	25
		3.	Companion Grids	25
	C.	Mechanical Properties of Brazed Joint		26
IV.	MAJOR PROBLEM AREAS			27
	A.	Poor Braze Quality		27
		1.	Description	27
		2.	Evaluation	27
		3.	Solution	27
	B.	Grid Verticality (Out-Of-Flatness)		28
		1.	Description	28
		2.	Evaluation	28
		3.	Solution	28
	C.	Blanket Grid Dimensional Problems		29
		1.	Description	29
		2.	Evaluation	29
		3.	Solution	29
V.	CONCLUSIONS			30
VI.	ACKNOWLEDGEMENTS			31
VII.	REFERENCES			31

LIST OF TABLES

Table No.	Title	Page
1	Chemical Analyses of Materials Used for LWBR Fuel Rod Support Grids	33
2	Composition of Cement Mixtures for Braze Alloy and Stop-off Application	34
3	Chemical Analyses of White Stop-Off Used for LWBR Grids	35
4	Dimensional Difference Between the Initial and Last Braze Cycle Measurements (Process A--NiCrFe Alloy 600 Brazing Fixtures)	36
5	AM-350 Sheet Metal and Wire Components Cleaning Procedure - Procedure A	37/38
6	AM-350 Bar Components Cleaning - Procedure B	39
7	Braze Alloy Quality After Brazing Cycle for One Module's Worth of Each - Seed, Blanket and Reflector LWBR Grids	40
8	Braze Joint Quality Acceptance Criteria for LWBR Grids	41
9	Metallographic Evaluation of Brazed Joints LWBR Seed Grid S/N 0020	42
10	Metallographic Evaluation of Brazed Joints LWBR Blanket Grid Type III (REM-3)	43
11	Metallographic Evaluation of Brazed Joints LWBR Reflector Grid S/N 5014	44

LIST OF FIGURES

Figure No.	Title	Page
1	LWBR Core Cross Section	45
2	LWBR Reactor Longitudinal Cross Section	46
3	LWBR Seed Rod Support Grid	47
4	LWBR Blanket Type I Rod Support Grid	48

LIST OF FIGURES (Cont)

Figure No.	Title	Page
5	LWBR Blanket Type II Rod Support Grid	49
6	LWBR Blanket Type III Rod Support Grid	50
7	LWBR Reflector Type IV Rod Support Grid	51
8	LWBR Reflector Type V Rod Support Grid	52
9	Nickel Base - 30 Chromium - 10 Silicon Braze Alloy Powder	53
10	LWBR Seed Grid Brazing Fixture (Exploded View)	54
11	LWBR Type II Blanket Grid Brazing Fixture (Exploded View)	55
12	LWBR 250 KW Vacuum Brazing Furnace	56
13	LWBR Brazing Furnace Vacuum System Operating Characteristics	57
14	Stop-Off Application on LWBR Grid Components	58
15	Braze Alloy Application on LWBR Grid Internal Segment Joints	59
16	Braze Alloy Application on LWBR Grid External Segment Joints	60
17	Braze Alloy Application on LWBR Grid End-Plates and Connector Joints	61
18	LWBR Seed Grid Assembly Fixturing	62
19	Braze Alloy Paste Application on LWBR Seed Grids	63
20	LWBR Blanket Grid Assembly	64
21	LWBR Blanket Type II Assembly Fixturing (Exploded View)	65
22	Braze Alloy Application on LWBR Blanket Grids	66
23	Braze Alloy Preplacement Inspection on LWBR Blanket Type III Grid	67

LIST OF FIGURES (Cont)

Figure No.	Title	Page
24	LWBR Simulated Hinge Joint Tensile Test Assembly	68
25	LWBR Seed Bottom Fixture Plate Installation	69
26	LWBR Type II Blanket Grid Brazing Fixture Assembly	70
27	Braze Thermal Cycle for LWBR Grids	71
28	LWBR Braze Alloy Hinge-Pin-Joints Quality Inspection at 10X Magnification on Seed Grids	72
29	Hinge-Pin Braze Joint Curl Designs for LWBR Grids	73
30	Braze Alloy Quality Inspection for LWBR Blanket Type III Grid	74
31	Braze Alloy Fillets Visual Standards for LWBR Grids	75
32	Longitudinal Cross Section Hinge-Pin End-Plate Connector Joint - LWBR Blanket Companion Grid 3169	76
33	Gamma Phase and Radial Crack in Beta Phase - LWBR Seed Companion Grid 0160	77
34	Transverse Cross-Section Hinge-Pin Connector Joint - LWBR Blanket Companion Grid 3169	78
35	Transverse Cross-Section Hinge-Pin Sheet Metal Closed Curl Joint - LWBR Blanket Companion Grid 3169	79
36	Transverse Cross-Section Hinge-Pin Sheet Metal Open Curl Joint - LWBR Reflector Companion Grid 4116	80
37	LWBR Reflector Companion Grid	81
38	Braze Hinge Joint Tensile Strength - LWBR Seed Grids	82
39	Braze Hinge Joint Tensile Strength - LWBR Blanket Grids	83
40	Braze Hinge Joint Tensile Strength - LWBR Reflector Type V Grids	84

A brazing process has been developed wherein several hundred stamped AM-350 stainless steel sheet metal components, wire components and machined bar components were simultaneously joined together to fabricate about 400 grids of different sizes for the LWBR fuel rod support system. High temperature (2110F ± 20F) vacuum brazing was employed using Ni-Cr-Si braze alloy filler metal in the form of paste. Techniques employed in the assembly, braze alloy application and fixturing of grids to achieve adequate dimensional control are discussed in detail. The brazing thermal cycle as related to the complex metallurgical process of both AM-350 stainless steel and the Ni-Cr-Si braze alloy is also discussed.

BRAZING OF AM-350 STAINLESS STEEL FUEL ROD SUPPORT GRIDS

(LWBR Development Program)

L. P. Ebejer

I. INTRODUCTION

The major objective of the LWBR core is to breed more new fissile material (uranium-233) from fertile material (thorium) than it consumes. In order to achieve this objective, cylindrical Zircaloy-clad fuel rods containing pellets of ceramic fuel and fertile material are precisely positioned in close-packed, triangular-pitch lattice arrays. The tight lattice spacing of the fuel rods is required to enhance neutron capture by the fertile material. At the same time, the rod-to-rod clearance necessary for the water coolant channel must be maintained to prevent fuel rod clad damage due to excessive surface temperatures. The support required to maintain the mechanical integrity of the fuel rods throughout the core life, while positioning the fuel rod array in a manner compatible with breeding, thermal, and hydraulic requirements was provided by: (1) Axial support that clamped one end of each rod to a base plate (2) Lateral support at specific elevations along the rods by passing each fuel rod through a support grid cell containing dimple and spring contacts.

The AM-350 stainless steel brazed grids provide the lateral support function of the fuel rod support system for the Light Water Breeder Reactor (LWBR) core (Reference 1). A cross-sectional view of the LWBR core is presented in Figure 1; a longitudinal view is shown in Figure 2. As indicated in Figure 1, the core consists of twelve hexagonally-shaped seed-blanket fuel modules in the central region, surrounded by fifteen reflector modules of either pentagonal or trapezoidal shape. The seed and blanket assemblies contain both fissile uranium-233 and fertile thorium-232, while the reflector blanket fuel modules contain only thorium.

The grids are axially bolted to Zircaloy-4 support posts through machined support-post connectors which are brazed to the grids. The blanket grids are also joined to the blanket guide tube by screws through tabs which are integral parts of the interior boundary straps. The configuration of the LWBR fuel rod support grids is illustrated in Figures 3 through 8.

The manufacture of LWBR fuel rod support grids required a process for joining several hundred stamped AM-350 stainless steel sheet metal components, wire components, and machined bar components in a manner consistent with precise dimensional control and acceptable metallurgical microstructures. The fuel rod support grids must be able to resist corrosion during service in a pressurized water nuclear power plant in addition to meeting stringent strength and close tolerance dimensional design criteria.

Brazing was selected as the most suitable method for the grid fabrication process due to the complex design of the grid structure. A description of the grid design and technical requirements and factors that led to the selection of AM-350 as the material of construction is presented in Reference 2. Brazing of the LWBR grids enabled the grids to be held together by two redundant mechanisms, thereby providing assurance that the grids would not come apart and block the coolant channels. The mechanical locking of pins after insertion through intersecting hinge curls of the grid components provided one mechanism. Brazing of the pins to the hinge curls provided a second mechanism for holding grids together, thereby imparting dimensional stability and rotational rigidity. The brazement also provided a smooth path for transmitting loads from grid component panels to the pins and hence to other panels. Thus many paths are available to transmit loads; consequently, the loads on grid elements are low, especially away from the connecting members.

The selection of a suitable brazing filler metal with characteristics compatible with the metallurgical characteristics of the AM-350 stainless steel base metal required extensive testing of BNi-5 and BNi-7 type braze alloys for brazeability and braze-joint corrosion resistance. Brazeability studies showed that although both types (BNi-5 and BNi-7) of braze alloys exhibited acceptable flow at their respective brazing temperatures, the lower degree of wetability of the BNi-5 alloys was suitable to bridge wide (approximately 0.010 inch) braze joint gaps. Thus only test joints made with BNi-5 braze type alloys were exposed to the LWBR test environments. After extensive corrosion testing of several braze alloys (Reference 3), a modified nickel base, 30 percent chromium, 10 percent silicon high temperature braze alloy was selected for use because of its superior corrosion resistance. Since a protective atmosphere and uniform temperature distribution were required during the heating, brazing, and cooling of the numerous joints, vacuum furnace brazing was selected to provide a controlled environment for brazing the AM-350 components.

The brazing filler metal (Ni-30 Cr-10 Si) forms a eutectoid with AM-350 stainless steel when heated to about 2100 F. Rigid fixturing during this thermal (brazing) treatment was required to support the thin (0.0135 to 0.018 inch) grid components at this very high temperature. In addition, the very tight design requirements for cell-to-cell pitch and boundary dimensions required the development of fixturing to retain all dimensions.

The grid fabrication process consisted of the following stages.

1. Assembly
2. Brazing
3. Decarburization
4. Subzero Cooling
5. Dimensional Inspection and Cell Adjustment
6. Tempering
7. Preconditioning
8. Machining
9. Final Dimensional Inspection and Cell Adjustment
10. Final General Inspection and Cleaning

The assembly and brazing operations of LWBR core fuel rod support grids represent the initial stages of the general grid fabrication process. This report discusses the development and process of the assembly and brazing operations.

II. MATERIALS, EQUIPMENT, AND PROCEDURES

A. Materials

1. AM-350 Precipitation Hardening Stainless Steel

The AM-350 sheet, bar, and wire material used for the fabrication of LWBR grid components was procured from air-melted, consumable electrode vacuum-remelted ingots. Compositional limits for the three forms of AM-350 were essentially identical except for the carbon content. The sheet material was made from bar stock having a carbon content of 0.06 to 0.10 weight percent, whereas the bar and wire material was specified to a lower carbon content of 0.04 to 0.07 weight percent. Corrosion studies (Reference 3) indicated that the lower carbon content enhanced the corrosion resistance of AM-350 by precluding the formation of grain boundary carbide precipitates during the decarburization operation.

AM-350 sheet stock, however, could not be purchased to the lower carbon content since lower carbon permits the normally ductile austenitic microstructure to be transformed (partially) to a less ductile martensitic microstructure during cold rolling from bar stock. The intricate forming operations for the components fabricated from the sheet material imposed considerable cold work, requiring a material of high ductility to prevent cracking and breaking. The sheet metal components were therefore stamped and formed from the higher carbon semi-austenitic AM-350 and then were decarburized to a nominal 0.04 weight percent following the decarburization operation (Reference 4). Because of their thicker cross sections, the bar and wire components were not readily reduced in carbon content in the decarburization operation and thus were purchased with the lower carbon content. This lower carbon content was also beneficial in assuring more complete transformation (from austenite to the higher strength martensite) for the thicker members during cool-down from the decarburization operation.

a. Sheet Metal Components

Stamped components 0.0135 to 0.018-inch thick were manufactured from hot- and cold-rolled, solution-annealed and descaled AM-350 sheet in flat lengths. All components were produced by room temperature stamping and forming operations using complex, multi-die commercial techniques. Samples of sheet stock were taken for chemical analysis prior to stamping operations to verify acceptable material composition. The analytical results are presented in Table 1.

b. Machined Bar Components

Grid connectors were machined from the low carbon AM-350 bar stock procured in the equalized and over-tempered condition. Prior to the machining of the connectors, samples were taken from each bar for chemical analysis to verify acceptable material composition. The analytical results are presented in Table 1.

c. Wire Components

Hinge pins were made from AM-350 wire which had been rolled, cold-drawn, solution-annealed, descaled and bright-drawn to finished diameters of approximately 0.036 and 0.045 inch. All wire stock was inspected for defects by eddy current techniques. The mean values of chemical analyses from sample wire lots are listed in Table 1. The wire was cold upset formed to produce a head on one end and then cut to the specified pin lengths. A machined chamfer was produced on the end of the pin opposite the head to preclude fissuring during the subsequent post-assembly crimping operation.

2. Brazing Filler Metal

Several commercially available braze alloys of Ni-Cr-Si (BNi-5) and Ni-Cr-P (BNi-7) types were evaluated for compatibility with the AM-350 base metal. Initial metallographic examinations of in-pile and out-of-pile tested Ni-Cr-Si (AMDRY-100 and J8100) brazed joints showed corrosion attack of the braze alloy fillets to varying depths. Corrosion was attributed to the oxidation of an interdendritic phase (high in nickel and silicon, low in chromium) referred to as gamma (γ) phase. To eliminate or disperse the corrodible gamma phase, extensive experiments were performed utilizing homogenization heat treatments, modification of braze alloy chemical composition, and reduction of braze joint clearances.

Brazed hinge joint studies showed that gaps larger than 0.010 inch exhibited poor braze quality due to voids, lower tensile strengths, and susceptibility to the formation of the undesirable corrodible gamma phase. Therefore, the stamped components were designed to provide a 0.006-inch maximum diametral gap between the hinge curl and the hinge pin to ensure high quality brazed joints.

Braze joint studies were also made with Ni-Cr-Si (AMDRY-100) braze alloy powders modified to contain higher chromium and silicon contents or modified by making various powder (Ni-Cr-Fe, Fe-Cr-Ni, and ZrO_2) additions to AMDRY-100 which nominally contains 19 Cr-10 Si-balance Ni. Braze joints made with these additions to AMDRY-100 did not exhibit any significant improvement in eliminating the corrodible phase. However, braze joints made with modified AMDRY-100 braze alloy (30 Cr-10 Si-balance Ni) showed both a reduction in and dispersal of the chromium depleted corrodible phase found in AMDRY-100 brazed alloy joints. Detailed corrosion evaluation of the brazing filler metals developed for use in LWBR is presented in Reference 3. The nickel base-30 percent chromium - 10 percent silicon braze alloy was selected for the LWBR grids. The mean values of analytical results of two braze alloy lots are presented in Table 1.

The brazing filler metal was manufactured as follows:

a. Raw Materials

1. Nickel - International Nickel Co., Inc. - Electrolytic grade.
2. Chromium - Shield Alloy Corporation - Vacuum Melted grade.
3. Silicon - Union Carbide Corporation - 99.5 percent Silicon, low Aluminum.

b. Process

The raw materials were weighed and placed in either a zirconium or alumina crucible for induction melting. The molten alloy was poured directly from the furnace into an atomizing device where it was atomized with argon and collected dry under an argon atmosphere. The powder was screened through a sieve size of -325 mesh maximum (Figure 9).

Argon atomization was necessary to produce low oxygen powders. Oxide-free spherical powders flow more readily into braze joints, enhance good brazing characteristics, and minimize the required brazing temperature.

3. Braze Alloy Binder

The nicrobraz braze alloy binder or cement was composed of an ethyl-methacrylate homopolymer mixed with a dichloroethane, trichloroethane solvent to a viscosity range of 350 to 450 centipoises. Composition of the cement mixture is presented in Table 2.

4. Stop-Off

White alumina stop-off powder was used as a barrier against uncontrolled braze alloy flow from the brazed joints onto the surfaces of the base metal. This is most important when brazing thin sheet metal structures to minimize structural distortion. Chemical analyses of the two stop-off powder lots used are presented in Table 3.

5. Stop-Off Cement

Stop-off cement used in the application of stop-off slurry was composed of an ethyl-methacrylate homopolymer mixed with a dichloroethane trichloroethane solvent to a viscosity range of 5 to 9 centipoises. Composition of the cement mixture is presented in Table 2.

B. Brazing Equipment

1. Fixturing

Ni-Cr-Fe Alloy 600 was selected for all braze fixturing because the thermal expansion characteristics of this material were most compatible with those of the semi-austenitic AM-350, which was braze-heat treated to remain semi-austentic during the braze cycle. Its selection was based on the results of an investigation of the thermal expansion and contraction, anisotropy, and dimensional stability characteristics of candidate brazing fixture materials for use in brazing/fabrication processes at temperatures up to 2100 F in vacuum (Reference 5). Alloy 600, which does not undergo phase transformation, displayed minimal dimensional change, cumulative shrinkage, and flatness change. An indication of the dimensional stability of Alloy 600 brazing fixtures with repeated usage was acquired by processing two fixture plates for 16 and 23 cycles, respectively, and noting the dimensional difference between the initial and last braze cycle measurements. These data, presented in Table 4 (which was extracted from Table 14 of Reference 5), demonstrate the stability of Alloy 600 fixture plates independent of their orientation relative to the final rolling direction. Based on these small changes (0.1 to 0.8 mil/inch range), it was concluded that Alloy 600 brazing fixtures would have useful shop lifetimes of 20-30 cycles.

Figures 10 and 11 show an exploded assembly view for seed and blanket grid brazing fixtures, respectively. The blanket brazing fixture required significantly more parts due to the shape and design of the blanket grid (blanket grids have a central hexagonal opening roughly the size of the seed grid). Though not shown, reflector grid brazing fixtures were comparable to the seed brazing fixtures.

Ni-Cr-Fe Alloy 600 spacer pins supported and maintained Parallelism of the brazing fixture plates. The grid support inserts were inserted into precisely located holes in the top and bottom brazing fixture plates, and held each grid cell panel normal to the top and bottom plates. The inserts were slotted to provide lateral restraint for the sheet metal components to prevent and/or minimize grid cell lateral distortion. The troughs precisely machined on the brazing fixture plates provided proper seating of all inserts which, in conjunction with the proper dimensioning of the spacers, controlled the flatness of the grids. It should be noted in Figure 11 that there is an additional baffle plate on top of the blanket grid brazing fixture. Studies determined this additional plate was necessary to provide uniform radial and vertical temperature gradients within these large, hexagonal, annular-shaped, blanket grids. The smaller sizes and non-annular shapes of the seed and reflector grids rendered this additional plate unnecessary. It should also be noted that blanket grid connectors were restrained by an adjustable wedge support system to prevent rotation and stem bending. A 304 stainless steel heat shield encloses the grid in the furnace to help maintain the even temperature distribution throughout the fixtured grid by protecting the outer boundary of the grids from direct radiation during heat-up and from Argon flow during cooling of the brazing cycle.

2. Brazing Furnace

The brazing furnace used for brazing LWBR grids is illustrated in Figure 12. It was a 250 KW, high temperature (2200 F) cold wall vacuum furnace equipped with forced convection cooling. The furnace consisted of a cylindrical stainless steel inner vessel surrounded by an outer water jacket. This horizontally positioned vacuum chamber was equipped with a water-cooled, dish-shaped hinged door sealed with an "O" Ring. The opposite end of the furnace was similarly sealed with an unhinged, water-cooled, dish-shaped head. A semi-automatic hot water system was provided for recirculating hot water in the furnace jacket to prevent condensation of moisture on the internal furnace chamber walls when the furnace door was open. During operation, cold water flowed through the water jackets maintaining the vessel at ambient temperature or lower, while the furnace was operating at elevated temperatures.

A movable hearth mechanism was used to transfer the fixtured grid into the furnace and from the brazing zone to the cooling zone during the accelerated cooling operation. The hearth assembly was mounted on grooved wheels that rode upon four parallel tracks mounted along the length of the inner vessel. A motor-driven chain moved the hearth cart assembly into and out of the heating and cooling zones, as required. The two zones of the furnace were separated by a pair of vertical heat barrier swinging doors which automatically opened when the load was moved from zone to zone and closed when the load was properly positioned in a particular zone.

A vacuum tight, high velocity, overhead fan was located in the cold zone of the furnace. This fan, in conjunction with an Argon back-fill system, permitted the grid to be rapidly cooled when positioned in the cold zone. This was accomplished by the fan and an atmosphere baffle. During this backfill operation, high purity Argon was uniformly pulled up through the grid and directed by the baffle such that the gas was forced to wipe the water-chilled chamber walls before returning to the bottom of the furnace. The cooled gas was then redirected upward through the grid.

The heating chamber was a cylindrical stainless steel frame lined with three layers of nickel and two layers of molybdenum radiation shields. Three 112-foot long, 83.33 KW molybdenum heating elements were positioned such that they completely surrounded (360 degrees) the work load. They were made of seven strands of molybdenum wire twisted into a cable. The cables were sinuously formed and secured in place by 112 high purity alumina spools which insulated the elements from the radiation shields. Power for the three furnace heating elements was supplied by a 250 KW power package consisting of three 83.33 KVA, 460V/100V transformers, and was regulated by three 83.33 KVA, 460 VAC/25 VDC saturable core reactors.

Furnace temperature was maintained by an electronic controller. Control signals were received from a sheathed "K" type thermocouple suspended from the furnace roof in the heating zone. The control instrument was a 3 set point proportional controller with rate and approach action. The control point was manually set with a setter knob to a digital read-out of 10 F. Deviation from the set point was clearly displayed on a zero center meter. To minimize thermal gradients across the fixtured grid, the controller was set to automatically regulate the power input at 55 percent between 200 and 800 F, 75 percent in the 800 to 1400 F range, and 100 percent full power above 1400 F. Grid temperatures were monitored and sequentially recorded on a 12-point strip chart continuously through the process cycle. Signals were received from six, 18-foot long, non-grounded junction, Ni-Cr-Fe Alloy 600 sheathed, chromel-alumel thermocouples strategically positioned in the fixtured grid. The thermocouples were purchased to requirements specified in ASTM-E-230-68, and calibrated to 1100 F and 1700 F or 1900 F and 2100 F temperatures. They were re-calibrated after every five braze runs to ± 10 F at 2100 F. An overheat controller provided a continuous visual indication of furnace temperature and protected against furnace overheating by automatically cutting off the heat input should the temperature have risen above 2200 F.

The vacuum pumping system of the furnace consisted of (1) A three stage 33000 liters per second diffusion pump (2) A 32-inch high conductance chevron baffle with a two stage mechanical refrigerator for maintaining -167 F cold trap temperature (3) A 685 CFM Roots type booster pump (4) A 162 CFM mechanical pump (5) An 18 CFM holding pump. The vacuum level of the furnace was measured in the roughing range of 1 to 1,000 microns by a thermocouple gauge, and in the high vacuum range of 10^{-3} to 10^{-7} torr by a cold cathode ionization gauge. Vacuum level during both roughing and high vacuum operation was continously recorded on a strip chart. The operating characteristics of the vacuum pumping system are illustrated in Figure 13.

C. Procedure

1. Component Cleaning

Sheet metal and wire components were cleaned utilizing Procedure A outlined in Table 5. Basically, this procedure consisted of vapor and solvent degreasing, alkaline cleaning to remove soil products from the metal surface, ultrasonic 15-20 V/O HNO_3 pickling to remove iron oxides, followed by passivation using a solution of 5 W/O $NaCr_2O_7$: $2H_2O$ in 20 V/O HNO_3.

The machined bar components were cleaned utilizing an acid free Procedure B (see Table 6) since the lower carbon bar material was received in an aged martensitic condition, which would oxidize in the cleaning Procedure A acid solutions. Procedure B consisted of dry abrasive cleaning to remove iron-oxides, followed by vapor-solvent degreasing and alkaline cleaning.

Cleaned components were inspected, packaged in polyethylene bags, sealed, and stored.

2. Stop-Off Application

Cleaned components were laid out on stainless steel trays in separate compartments in sufficient quantities for each different type of component (Figure 14). A stop-off slurry was prepared by blending 30 $\pm$ 1 grams Nicrobraz white stop-off, 30 $\pm$ 2 milliliters of Nicrobraz cement (5 to 9 centipoises viscosity grade), and 30 $\pm$ 2 milliliters acetone in a glass beaker. The slurry was stirred continuously during use with a magnetic stirrer and magnetic stirring bar to assure a thin, adherent, smooth, milky film when applied to the components. Dilution of stop-off slurry by adding 5 milliliters of acetone was made when the film become discontinuous or lumpy due to settling of aluminum oxide particles. An artist's brush was used to apply stop-off along the entire length of all the side panels of the components. The components were then individually inspected to ensure that no stop-off was present in hinge curl areas where braze joints eventually were to be formed.

3. Grid Assembly and Braze Alloy Application

During the early stages of the grid fabrication program, braze alloy was applied after each cell was assembled for all grid types. Measurements on the first four Type V reflector alloyed grids, prior to brazing fixture installation, showed that perpendicularity and flatness did not satisfy process control requirements. Consequently, a new technique was used to completely assemble the reflector and blanket grids and then apply braze alloy. Seed grids, however, were assembled and braze alloy was applied sequentially utilizing a technique described in the following paragraphs.

Braze alloy paste was prepared by thoroughly blending 20 ± 0.1 grams of nickel base, 30 percent chromium, 10 percent silicon powder and 6 ± 0.1 grams of Nicrobraz cement binder (350 to 450 centipoises). The paste was stirred vigorously with a glass rod to ensure complete wetting of the braze alloy powder and then transferred to a plastic syringe using a scoopula. A rubber piston and syringe needle were inserted into the syringe. This syringe was connected to a foot-controlled, air-operated, micro air dispenser, which, in turn, was attached to a pressure regulator adjusted to a range of 10 to 35 psig.

Braze alloy paste application was performed with the seed grids in a 45 degree angle position and the hinge joint areas (shown in Figures 15 through 17) facing upwards. The braze alloy paste flowed down into the joint and was permitted to freeze before the grid was repositioned.

The established assembly technique for seed grids was performed as follows:

a. The center cell and a surrounding ring of cells were assembled and braze alloy applied to the center cell only.

b. A set of two cells along each side of the six diagonals were subsequently assembled.

c. The spider-like fixture and inserts (shown in Figures 18 and 19) were installed to hold subsequent grid assembly sections perpendicular to the assembly plexiglass plate. Braze alloy paste was then applied to the diagonal cells.

d. The balance of the grid was then assembled and braze alloy was applied in a spiral fashion until the grid was completely assembled and alloyed.

Blanket and reflector grids were assembled horizontally as shown in Figure 20 for blanket Type II grids. The assembly fixture details are illustrated in Figure 21. When the grids were completely assembled, right angle external wall holding fixtures were installed against the grid boundaries and bolted to the turntable fixture through the plexiglass assembly plate. The clip assemblies were then installed on top of the external grid periphery and clamped to hold the grid flat to maintain verticality of the external grid walls during braze alloy application. The inner wall holding fixture shown in Figure 21 was used to maintain verticality for the internal grid boundary. The assembled and fixtured grids were then lifted to a vertical position and braze alloy was applied as shown in Figure 22. When placement of the braze alloy on the grid was completed, the joints were inspected with an illuminating magnifying glass, as shown in Figure 23, to ensure that braze alloy was present in all the hinge joint areas. Braze alloy was re-applied to any areas needing repair, using the same braze alloy slurry mixture described above. The repaired areas were then re-inspected.

A small grid assembly consisting of a minimum of ten cells, two representative external boundary sections and a connector (see Item 3 in Figure 11) was also assembled and braze alloy was applied in the same manner. This companion grid was processed through each stage of fabrication, that is, assembly, brazing, and heat treatments in the same equipment, with equivalent fixturing, and at the same time as the grid it represented. This companion grid was used for destructive evaluation to determine the quality of the brazed joints and the metallographic structure of the full-sized grid it represented.

Two hinge joint tensile test assemblies (Figure 24) simulating brazed hinge-pin joints in the grids were assembled with braze alloy applied to the open and closed curls of the joint. These two assemblies were processed through brazing and heat treatments with the grid they represented. These assemblies were later used for destructive evaluation to determine tensile properties of the brazed joints of the grid they represented.

4. Fixturing of Alloyed Grids

The alloyed grids were placed with the grid pin heads down, on an assembly stand plate as shown for a seed grid in Figure 25. The bottom brazing fixture was placed over the grid and supported by spacers. When the grid was aligned with the bottom brazing fixture, inserts were installed at the center of the grid in a hexagonal array. Six inserts were then installed at each of the six corners of the fixture. The continuation of insert installation was done by working from the center of the fixture and filling in the pie-segments in an ever-increasing hexagonal pattern Upon completion, a backing plate was placed over the inserts and the grid and brazing fixture were inverted.

Prior to installation of the top brazing fixture, the grid was inspected for braze alloy dislodgement with the illuminating magnifying glass.

The top brazing fixture plate was supported by spacers and spacer pins. A lock pin was installed through the four corner spacers and secured with a wedge. After verifying that the top and bottom fixture plates were aligned, inserts were placed from the center of the fixture plate in an outward direction. Figure 26 shows a blanket Type II fixtured grid ready for brazing. Stop-off slurry was poured over the bottom brazing fixture and backing plates to prevent the fixtures from sticking to the furnace hearth. This slurry was prepared by blending 30 ± 5 grams of Nicrobraz white stop-off, 30 ± 5 milliliters of Nicrobraz cement (5 to 9 centipoises viscosity grade), and 75 ± 5 milliliters of acetone.

The companion grids were fixtured for brazing in the same manner as the full-size grids.

5. Brazing

a. Furnace Loading and Pumpdown

The grid, its companion grid sections, and hinge pin tensile test assemblies were loaded on a cart-mounted hearth near the furnace door. Six thermocouples were positioned and secured in various locations: four thermocouples were positioned adjacent to grid sections to monitor the grid and two were positioned in the braze plates.

After ensuring that thermal and vacuum systems were functioning properly, the loaded work cart was transferred into the cooling zone and secured to the transfer chain. The cart was then moved into the hot zone, the furnace door was closed, and the latches were secured. The vacuum control was turned to the roughing position for pumpdown until 20 microns vacuum pressure was achieved. The vacuum selector switch was set at the "Fore" position until a 10 to 20 micron pressure level was stabilized. The vacuum range selector was then changed to the "Hi-Vac" position to engage the diffusion pumps and pump down the furnace to 3×10^{-5} torr. The furnace was then checked for leaks by turning the vacuum selector switch to the "Fore position for one minute, allowing the pressure to rise. If 5×10^{-4} torr pressure was exceeded, the furnace was examined for leaks and repaired prior to returning the vacuum switch to "Hi-Vac" and continuing the operation.

b. Thermal Cycle

Heat was turned on when a vacuum of 3×10^{-5} torr was stabilized. Initial heat-up to 1830 F was in incremental steps of 200 ± 50 F to minimize temperature differentials throughout the fixtured grid. At each incremental temperature, equilibration of temperature was maintained within 150 F, with the pressure at 9.0×10^{-4} torr or less. It was important to maintain these conditions in order to remove or prevent the formation of any absorbed surface films that may have been present on the AM-350 metal prior to heat-up to brazing temperature. Heat-up from 1100 F to 1830 F was limited to a maximum of four hours. To minimize reactions between the AM-350 base metal and braze alloy, that is, forming of nickel-silicon rich eutectic at the AM-350 base metal surface and erosion of the AM-350 base metal by the molten braze alloy, "heat-up" from 1830 F to the brazing temperature of 2110 ± 20 F was done rapidly within a maximum of 60 minutes. The hold time at brazing temperature was monitored by the 4 grid thermocouples and was maintained from 5 to 15 minutes. In addition to keeping the braze alloy AM-350 base metal erosion to a minimum, the holding time at brazing temperature was kept at the lower range to minimize nitrogen losses from the AM-350 base metal by outgassing since nitrogen is an alloying element (austenite former) in AM-350. The brazing temperature hold time did not exceed 15 minutes to prevent delta ferrite grain growth and formation of intermetallic compounds in the brazed joints.

Cooling from the brazing temperature to 1710 ± 30 F was done in the furnace hot zone, under vacuum, maintaining a temperature differential between all thermocouples in the workload within 150 degrees to minimize thermal differences between the thin grid structures and the heavy fixture plates. When all thermocouples reached the 1710 ± 30 F temperature range, the furnace was backfilled with Argon and the work charge moved to the furnace cold zone to achieve cooling down from 1710 F to 1100 F within 20 to 40 minutes. This cooling rate was required to prevent chromium carbide precipitation along the AM-350 grain boundaries and to retain the carbon in solution in the AM-350 base metal, thus keeping the martensite transformation temperature suppressed. During continued cooling to 300 F ± 50 F, the fan was operated intermittently to maintain the temperature differentials between all thermocouples within 200 F.

When the fixtured grid reached a temperature between 250 F and 350 F, the furnace door was opened, the grid was transferred rapidly to a tank, and immersed in hot water maintained at 200F minimum until the grid was removed from the fixture. This was done to prevent martensitic transformation of the grid while it was held in the fixture. Transformation results in about 0.004 inch/inch growth; if this occurred while the grid was still in the fixture, excessive cracking along the braze joint fillets could have resulted. A corollary benefit of disassembly in hot water was that it provided a lubricating action during removal of the brazing fixture inserts from the braze plates and the grid. Figure 27 shows the braze thermal and vacuum cycles for brazing LWBR grids.

III. RESULTS

A total of 147 seed, 164 blanket, and 118 reflector grids were brazed by the process described in Section II. There was no evidence of surface attack or any other detrimental effect on the AM-350 base metal as a result of the brazing process; this is supported by the bright metallic appearance of the grids after brazing. An excellent degree of flatness and parallelism was achieved on the brazed grids by controlling perpendicularity and flatness during braze alloy application with holding fixtures and during brazing by the brazing fixtures.

Seed and reflector grids met the expected external boundary dimensional design attributes and requirements after brazing. Blanket grids exhibited oversize external boundary dimensions. Although it was minimized somewhat, this problem continued even after extensive development effort on brazing fixture redesign. This condition was corrected, without degrading the internal grid design dimensional attributes, by a subsequent process step termed "temper-sizing."

The braze quality with regard to flow and bonding was exceptionally good for all grids. Only one seed, one blanket, and four reflector grids were rejected for poor braze quality. Poor quality was primarily the result of lack of braze alloy preplacement in the early part of the brazing development program. This was later corrected.

A. Visual Examination of Brazed Joints

Visual inspection was performed at 5X magnification for seed grids and 10X for blanket and reflector grids. Inspection was done with the grids in the near-vertical plane using a stereo-microscope with fluorescent back lighting as shown in Figure 28. Figure 29 shows the hinge-curl joint types found in the hinge-pin joints. The braze evaluation plan involved inspection of the three top and bottom hinge-pin-curl joints at all hinge-pins defined as critical, and a sample evaluation of hinge-pins defined as non-critical (Figure 30). As defined below, joints were evaluated for braze cracks, braze flow/bond quality, porosity, and fillets.

1. Braze cracks were revealed as "hairlines" generally running longitudinally in the direction of the hinge-pin and extending over a fraction or the total length of the curl. They were relatively straight and unjagged and were usually associated with large braze joint gaps which were not adequately filled with alloy.

2. Adequate braze flow and bond quality were evidenced by a uniform braze appearance, smoothness of braze flow, and the presence of some fillets. Inadequate braze flow and bond quality were characterized by non-uniform (rough) appearance, lack of smooth fillets, and porosity due to improper melting resulting from too low a brazing temperature or contaminated braze alloy. Figure 31 shows examples of good and poor braze flow/bond quality.

3. Filleting provided overall evidence of an adequate brazing temperature, clean components, and the presence of an adequate quantity of braze alloy. Figure 31 shows an example of a pin-curl with poor braze fillet. Pin head-to-curl and crimp-to-curl joints were inspected to determine the presence of braze alloy as evidenced by partial or continuous fillets.

4. Table 7 shows the braze alloy quality for the first 12 seed grids, the first eight blanket, and the first six reflector grids. The relatively high incidence of cracks in reflector grids was partially due to insufficient braze alloy preplacement which was corrected in later grids.

Another postulated reason for the excessive cracking in reflector grids was that in some grids, phase transformation of the AM-350 base metal from austenite to martensite occurred. This resulted in growth of 0.004 inch/inch and a build-up of stresses in the larger diameter 0.045-inch reflector hinge joints as opposed to 0.030-inch diameter seed and blanket hinge joints. In seed and blanket grids, braze cracking was attributed to insufficient braze alloy preplacement and difficulty in removing connector block supports from the seed grids during hot lift-off operation.

Fatigue tests of full size seed, blanket, and reflector grids were performed to determine the load bearing capability of the grid as a function of cyclic loading and the initial and final number of braze defects. The test results indicated that the load deflection characteristics of the grids were not affected by the typical range of braze quality, even though the number of braze cracks at critical joints were in some cases greater than the defined limits. As a consequence, the acceptance criteria were deleted for non-critical joints, and only the critical joints were inspected on later grids. Braze joint acceptance criteria are listed in Table 8.

B. Metallographic Properties

1. Microstructure

Typical microstructure of a brazed joint is shown in Figure 32. In this figure, the longitudinal section of a connector joint, taken from companion test grid 3169 at 10X magnification, shows good braze fill and bonding with minimal scattered porosity. Figure 32 shows that base metal erosion and/or dilution were not significant. The two distinct phases, alpha and beta, were analyzed by electron microprobe analysis. The basic matrix, beta, was a solid solution containing Ni-Cr-Si-Fe and is richer in Cr and Ni than the alpha phase. The corrodible phase denoted as gamma in Figure 33 is depleted in Cr and Fe, but enriched in Ni and Si. The small angular phases at the interface are nickel-chrome carbides and nitrides formed by the carbon and nitrogen diffusion from the base metal to the braze alloy. The carbides and nitrides were found to be innocuous in regard to the mechanical and corrosion properties of the brazed joints as described in Reference 4. Count rates obtained for each structure for Cr, Fe, Ni, Si, and Ti and Mo were confirmed by X-Ray image photographs and are listed below:

Element and Line	Beta Phase	Alpha Phase	Gamma Phase	Triangular Phase(s)
CR K ALPHA	2,229 CPS	2,088 CPS	585 CPS	4,700 CPS
FE K ALPHA	1,590 CPS	2,340 CPS	675 CPS	463 CPS
NI K ALPHA	6,750 CPS	7,430 CPS	10,260 CPS	4,630 CPS
SI K ALPHA	318 CPS	198 CPS	462 CPS	316 CPS
TI K ALPHA	---	---	---	29 CPS
MO L ALPHA	5 CPS	---	---	29 CPS

In grids where the nickel-silicon rich, chrome depleted gamma phase was observed, the areas were small (less than 0.002 inch by .002 inch) and restricted to the center of the joint. There were no instances of the gamma phase being prevalent at the surface of the braze joint fillet where it would come in contact with the reactor water environment and possibly lead to accelerated corrosion. Radial cracks were observed in many joints but these were restricted to the center beta phase, where they do not affect the structural integrity of the braze joint. Figures 34, 35, and 36 show acceptable transverse sections of closed and open curl joints.

2. Preproduction Grids

One seed preproduction grid, one blanket Type III preproduction grid, and one reflector Type V preproduction grid, processed and brazed in the same manner as grids used in LWBR, were sectioned for metallographic evaluation of brazed joints. Twelve longitudinal sections (each section containing five closed and four open curls) and 48 transverse sections from each grid were examined. The braze quality and bond lengths in sheet metal joints were particularly good. Braze flow and bonding was marginal for seed and reflector grids in connector joints. This was due to lack of adequate amounts of braze alloy preplacement at the inaccessable joints after boundary strap-endplate welding rather than to wetability of braze alloy over the AM-350 base metal. The solution to this problem for blanket grids was preplacement of the alloy at those joints prior to spot-welding of boundary straps to endplates. This provided an adequate quantity of braze alloy and assured good braze flow and bonding at those joints. Two longitudinal cracks found in the seed joints examined were also related to lack of braze alloy preplacement. Six circumferential cracks in the seed, one in the blanket, and three in the reflector grid were found in the joints examined. Tables 9 through 11 show the results of metallographic evaluation of brazed joints for the three preproduction grids.

3. Companion Grids

Each companion grid processed with each core grid was sectioned as illustrated in Figure 37. Blanket and reflector grids showed very good brazed bond joints and braze quality. However, as noted above the first sixty seed grids showed some lack of braze in the connector joints that meet with boundary strap-endplate curls due to the difficulty in braze alloy preplacements; later grids had satisfactory joints. Circumferential and longitudinal cracks in twelve seed grids were also associated with lack of braze alloy preplacement. The lower amount of braze alloy fill in seed grid connectors was found to have no significant effect on the fatigue performance of the grid structure. Fatigue tests are described in Reference 6.

C. <u>Mechanical Properties of Brazed Joints</u>

Simulated braze hinge joint specimens for the three types of grids (Figure 24) were used for tensile testing of the braze alloy. A universal tensile testing machine was used with a cross-head speed of 0.05 inches per minute. Minimum requirements for tensile strengths were based on several types of braze joint specimens using various grid configurations tested for tensile and fatigue properties. Since specimens tested at 600 F had a decreased tensile load and fatigue strength compared to room temperature tests, the companion braze joint assemblies for the first module's worth of seed, blanket, and reflector grids were tested at 600 F. The reported values shown in Figures 38, 39, and 40 were the loads at which the load deflection curve showed a reduction with increasing deflection which exceeded 10 percent of the load at that point or 20 lbs, whichever was greater. The average tensile strengths were well above the minimum requirements.

In summary, the static tensile strengths of the hinge-pin joints were high in comparison to calculated design loads in seed, blanket, and reflector grids. This confirmed the structural adequacy of the support grids in terms of static considerations; the calculated stresses for design cyclic requirements were substantiated by fatigue testing of actual grids (Reference 6).

IV. MAJOR PROBLEM AREAS

A. Poor Braze Quality

1. Description

During the early grid fabrication process, braze quality was poor. Difficulty was also experienced during braze alloy application due to the separation of braze alloy powder from the slurry.

2. Evaluation

The principal cause for this was attributed to poor homogenization of the braze alloy slurry, resulting in lack of adhesion to hinge joints after application. Subjecting the grid to minor mechanical shocks during subsequent fixturing and loading in the furnace caused the braze alloy to slough-off before the grid was brazed.

3. Solution

Braze alloy powder mesh size was screened to a maximum of -325 mesh size to increase surface area, while at the same time the resin content of the Nicrobraz cement was increased to meet a cement viscosity of 400 $\pm$ 50 centipoises. Thoroughly mixing the braze alloy slurry in small quantities (20 grams of alloy powder to 6 grams of Nicrobraz cement) provided better fill, adhesion, and shelf life in the grid hinge-pin joints. Braze alloy slurry separation or spalling off prior to brazing no longer occurred after these braze alloy corrective actions were implemented.

B. Grid Verticality (Out-Of Flatness)

1. Description

External and internal boundary-strap endplate weldments of the first lead blanket and reflector grids were severely tilted resulting in post braze violations of cell-to-cell dimensions and endplate verticality.

2. Evaluation

The first four reflector Type V and the first three blanket lead grids had braze alloy applied as each cell was assembled in a near vertical position. The assembled and braze alloyed grid peripheral sections, being unrestrained, tilted away from the assembly plate before the braze alloy hardened. This caused the grid to have an out-of-flatness condition compared with the outer peripheral cells. Thus, the installation of the edge brazing fixture inserts was difficult and a build-up of stresses during grid fixturing occurred.

3. Solution

In order to overcome the verticality problem, external wall holding fixtures and internal (blanket grids only) fixtures were introduced. Grids were assembled completely flat in a horizontal position. The new fixtures restrained the grid such that during braze alloy application at a near vertical position the grid was held perpendicular to the assembly plate until the alloy hardened. When the fixtures were removed, verticality and parallelism of the grid were still maintained. The modified technique of assembling grids, installing assembly holding fixtures, and braze alloy application of the fixtured grids greatly improved the flatness and parallelism of the brazed blanket and reflector grids.

C. Blanket Grid Dimensional Problem

1. Description

Analyses of development Type III blanket grid dimensional data indicated three major problems: (1) Oversize outer and inner boundary dimensions (2) Clearance violations between fuel rods and walls of grid cells along the inner and outer boundaries (3) Sagging and rotation of grid connectors during brazing.

2. Evaluation

A study of this blanket dimensional problem concluded that the major cause of the boundary deviations and of the proximity problem was the large temperature differential encountered between the brazing fixture plates and the grid, and within the grid during brazing cooldown. Grid connectors were also sagging and rotating during brazing; this caused the external boundary dimensions to increase significantly.

3. Solution

Brazing fixtures and inserts were modified extensively to resolve dimensional distortion problems in the blanket grid program at the inner and outer boundaries of these grids as described below:

a. The top and bottom brazing fixtures were redesigned with a built-in inner hexagon perforated solid plate to protect inner grid boundaries from direct radiation and reduce the argon flow in the center, thereby better equalizing the cooling rate throughout the grid. In addition, a baffle plate was added on top of the top braze plate (see Figure 11, Item 1).

b. The slots of inserts were lengthened to eliminate the "thumbnail" distortion of the spring panel.

c. Long clothespin-type inserts (Figure 11, Item 18) replaced the cantilever-type insert to box in the boundary and eliminate the freedom inherent in the cantilever-type insert which allowed the grid to move outward. These inserts were employed on all sides of the grid.

d. A triple insert was designed to combine the blocking characteristics of the back-stop insert with the capability of holding the spring panel. These inserts replaced the back-stop inserts to prevent panel bowing noted where back-stop inserts were used. Backing slats (Figure 11, Item 21) (part of the triple insert) were used to prevent outer bowing.

e. Connector wedge and wedge supports (Figure 11, Items 11, 12, 13, and 14) were installed with a 0.001-inch minimum clearance to prevent rotation and sagging of connector lugs.

f. Internal corner blocks (Figure 11, Item 17) and padded "thru" inserts were employed at the inner boundary. The internal blocks prevented bulging at the six corners of the inside hexagon while the padded "thru" inserts helped to resolve the internal boundary distortions at the tab locations.

V. CONCLUSIONS

A. Brazing of AM-350 fuel rod support grids with nickel base 30 percent chromium, 10 percent silicon braze alloy was successfully achieved and controlled utilizing special vacuum furnace brazing techniques.

B. High quality braze joints were achieved to accommodate high dynamic loads by limiting diametral gaps in the hinge-pin joints to less than 0.010 inch.

C. Ni-Cr-Fe Alloy 600 brazing fixtures can be used at brazing temperatures of 2110 F ± 20 F for about 16 to 24 cycles when brazing AM-350 stainless steel. However, fixtures must be removed in hot water (200 F) to prevent deleterious effects to brazed joints due to dimensional mismatches caused by partial martensitic transformation of AM-350 when cooled to room temperature.

D. Ni-30 Cr-10 Si braze filler metal of -325 to -400 mesh size can provide good flow and wetting properties during braze temperatures ranging from 2090 F to 2130 F when used with AM-350 stainless steel.

VI. ACKNOWLEDGEMENTS

The author wishes to recognize his many colleagues who assisted in the technical preparation and review of this document. In particular the author is indebted to R. M. Glass, K. D. Richardson, J. W. Barbour, B. Z. Hyatt, J. S. Blay, B. R. Gourley, H. M. Schadel, Jr., R. J. Towner for their contributions to the overall technical effort. A special thanks to J. E. Marnell of Central Drafting, Bettis Atomic Power Laboratory for preparing all illustrations.

VII. REFERENCES

1. D. R. Connors, et al, "Design of the Shippingport Light Water Breeder Reactor," WAPD-TM-1208, January, 1979.

2. K. D. Richardson, "Summary of the Fuel Rod Support System (GRIDS) Design for LWBR," WAPD-TM-1331, February, 1979.

3. J. W. Barbour, "Corrosion Evaluation of Nickel-Base Brazing (LWBR Development Program)," WAPD-TM-1184, September, 1978.

4. B. R. Gourley, "Decarburization of AM-350 Stainless Steel LWBR Fuel Rod Support Grids (LWBR Development Program)," WAPD-TM-1131, February, 1977.

5. R. J. Towner, "Brazing Fixture Materials for Fabrication of AM-350 Fuel Rod Support Grids," WAPD-TM-1063, August, 1976.

6. Shippingport Atomic Power Station Safety Analysis Report for the Light Water Breeder Reactor, Volume 1, pp. 64-65, 1975.

TABLE I

CHEMICAL ANALYSES OF MATERIALS USED FOR LWBR FUEL ROD SUPPORT GRIDS

ELEMENT	AM-350 PRECIPITATION HARDENING STAINLESS STEEL					Ni-30 CR-10 SI BRAZE ALLOY w/o	
	SHEET w/o		BAR w/o		WIRE w/o		
	HEAT 39647	HEAT 75477	HEAT 28614	HEAT 28339	HEAT 27880	LOT 1410	LOT 1585
CARBON	0.080	0.074	0.045	0.044	0.0437	0.017	0.0106
MANGANESE	0.69	0.079	0.73	0.65	0.734	0.02	<0.02
PHOSPHORUS	0.023	0.024	0.015	0.013	0.029	0.003	0.010
SULFUR	0.011	0.005	0.018	0.022	0.013	<0.005	0.008
SILICON	0.30	0.26	0.23	0.27	0.35	9.94	10.06
CHROMIUM	16.65	16.64	16.57	16.84	16.84	30.45	30.35
NICKEL	4.30	4.22	4.19	4.36	4.32	58.54	59.34
MOLYBDENUM	2.82	2.77	2.62	2.73	2.67	–	–
COBALT	–	0.073	0.042	<0.002	0.027	0.01	<0.05
NITROGEN	0.093	0.088	0.060	0.075	0.071	0.066	0.046
BORON	–	0.001	0.004	<0.005	0.0017	<0.001	<0.005
IRON	BALANCE	BALANCE	BALANCE	BALANCE	BALANCE	<0.28	<0.25
ALUMINUM	–	–	–	–	–	<0.02	<0.015
TITANIUM	–	–	–	–	–	<0.02	<0.015
ZIRCONIUM	–	–	–	–	–	0.005	<0.015
OXYGEN	–	–	–	–	–	511 ppm	269 ppm

TABLE 2

INFRARED SPECTROSCOPY AND GAS CHROMATOGRAPHY ANALYSES OF BRAZE ALLOY AND STOP-OFF CEMENT

	BRAZE ALLOY CEMENT NICROBRAZ 400	STOP-OFF CEMENT NICROBRAZ 500
SOLIDS PERCENT	19.5	3.61
SOLIDS COMPOSITION	ETHYLMETHACRYLATE HOMOPOLYMER	ETHYLMETHACRYLATE HOMOPOLYMER
VOLATILES COMPOSITION BY WEIGHT		
1,2 – DICHLOROETHANE	54.1%	18.0%
1,1,1 – TRICHLOROETHANE	44.9%	81.0%
1,1 – DICHLOROETHANE	1.0%	1.0%

TABLE 3

CHEMICAL ANALYSES OF WHITE STOP-OFF USED FOR LWBR GRIDS

ELEMENT	LOT 148	LOT 170
CHLORINE	<100 ppm	<100 ppm
FLUORINE	< 20 ppm	< 20 ppm
SULFUR	<200 ppm	<200 ppm
PHOSPHORUS	< 50 ppm	< 50 ppm
BORON	< 10 ppm	< 10 ppm
ARSENIC	<100 ppm	<100 ppm
ANTIMONY	<100 ppm	<100 ppm
MERCURY	< 10 ppm	< 10 ppm
COPPER	< .01%	< .01%
IRON	.01%	.01%
MAGNESIUM	< .01%	< .01%
MANGANESE	< .01%	< .01%
SILICON	.5%	.2%
CALCIUM	.01%	.01%
SODIUM	.05%	.05%
ALUMINUM OXIDE (Al_2O_3)	BALANCE	BALANCE

TABLE 4

DIMENSIONAL DIFFERENCE BETWEEN THE INITIAL AND LAST BRAZE CYCLE MEASUREMENTS (PROCESS A–NiCrFe ALLOY 600 BRAZING FIXTURES)

FIXTURE	ORIENTATION WITH RESPECT TO ROLLING DIRECTION	NO. OF CYCLES	TOP PLATE		BOTTOM PLATE	
			MILS	MILS/INCH	MILS	MILS/INCH
BA-2 S/N-01	PARALLEL	16	+4.0	+0.3	+2.0	+0.1
BA-2 S/N-01	PERPENDICULAR	16	+1.6	+0.1	+2.0	+0.1
BA-1 S/N-02	PARALLEL	23	+12.5	+0.8	+4.0	+0.3
BA-1 S/N-02	PERPENDICULAR	23	+2.0	+0.1	+5.5	+0.3

TABLE 5

AM-350 SHEET METAL AND WIRE COMPONENTS CLEANING PROCEDURE
PROCEDURE A.

a. Degrease parts in the solvent vapor phase for 10 to 15 minutes, spraying at 4 minute intervals with cold distillate.

b. Ultrasonic degrease parts for 5 minutes in solvent at room temperature.

c. Repeat a above.

d. Repeat b above.

e. Repeat a above.

SOLVENT

Perchloroethylene stabilized with a neutral inhibitor.

↓

Alkaline clean parts in aqueous air-agitated solution.

Alkaline Solution

a.	Materials	Amt./gal. of Solution
	Trisodium phosphate (anhydrous)	7 to 10 oz.
	Nonionic detergent, Triton X-100	1 oz.
	Water, Grade B (or better)	Balance
b.	Operating temperature	190 ± 10°F
c.	Time of immersion	25 ± 5 minutes

↓

a. Cold spray rinse parts with grade B water or better beginning as parts break the surface and continuing with work basket placed on drain rack.

b. Immersion rinse parts in double cascade flow cold grade B water or better with surface overflow.

NOTE: Parts shall be free of water breaks after rinsing.

↓

Nitric-Acid Pickle parts in ultrasonic agitated solution.

Pickling Solution

a.	Materials	Amt./gal. of Solution
	Nitric acid, nominal 70 w/o Assay 1.42 Sp. Gr.	650 milliliters (15-20 v/o)
	Water, Grade A	Balance
b.	Operating temperature	150 ± 5°F
c.	Time of immersion	30 ± 3 minutes

↓

a. Cold spray rinse parts with grade B water or better beginning as parts break surface. Hold rinsing time to a minimum, enough to prevent parts from drying in transit to passivating solution dip.

NOTE: Parts shall be free of water breaks after rinsing.

↓

Sodium-Dichromate-Nitric Acid – Dip parts in an agitated passivating solution.

Passivating Solution

a.	Materials	Amt./gal. of Solution
	Nitric acid, nominal 70 w/o Assay 1.42 Sp. Gr.	750 milliliters (20 v/o)
	Sodium Dichromate Dihydrate	7 oz.
	Water, Grade A	Balance
b.	Operating temperature	110 ± 10°F
c.	Time of immersion	30 ± 5 minutes

↓

a. Cold spray rinse parts with grade B water or better as parts break the surface and continuing with work basket placed on drain rack.

b. Immersion rinse parts in double cascade flow cold grade B water or better with surface overflow.

NOTE: Parts shall be free of water breaks after rinsing.

↓

Neutralizing Solution – Dip parts in solution agitated by air or by hand.

Neutralizing Solution

a.	Materials	Amt./gal. of Solution
	Trisodium phosphate (anhydrous)	1 oz.
	Water, grade B or better	Balance
b.	Operating temperature	190 ± 10°F
c.	Time of immersion	1 to 2 minutes

↓

a. Cold spray rinse parts with grade B water or better as parts break the surface and continuing with work basket placed on drain rack.

b. Immersion rinse parts in triple cascade flowing water with surface overflow. Final rinse compartment has influent grade A water maintained at 190 ± 10°F. Work basket held 15 ± 5 minutes in each compartment.

NOTE: Parts shall be free of water breaks after rinsing.

↓

Dry parts in a convective air current oven at 200 to 225°F for a minimum of 15 minutes.

↓

WATER PURITY

GRADES	A	B
Chlorine, maximum ppm	0.1	1.0
Conductivity, maximum microohm/cm	2.5	20
pH range	6.0 - 8.0	–
Visual Clarity	No turbidity, oil or sediment	

TABLE 6

AM-350 BAR COMPONENTS CLEANING PROCEDURE
PROCEDURE B.

DRY ABRASIVE CLEANING

a. Hand polish parts with Al_2O_3 1200 grit paper.

b. Blow parts with argon at approximately 40 p.s.i. under a hood with an exhaust system.

↓

a. Degrease parts in the solvent vapor phase for 10 to 15 minutes, spraying at 4 minute intervals with cold distillate.

b. Ultrasonic degrease parts for 5 minutes in solvent at room temperature.

c. Repeat a above.

d. Repeat b above.

e. Repeat a above.

SOLVENT

Perchloroethylene stabilized with a neutral inhibitor.

↓

Alkaline clean parts in aqueous air-agitated solution.

Alkaline Solution

a. Materials	Amt./gal. of Solution
Trisodium phosphate (anhydrous)	7 to 10 oz.
Nonionic detergent, Triton X-100	1 oz.
Water, Grade B (or better)	Balance
b. Operating temperature	190 ±10°F
c. Time of immersion	25 ±5 minutes

↓

a. Cold spray rinse parts with grade B water or better as parts break the surface and continuing with work basket placed on drain rack.

b. Immersion rinse parts in triple cascade flowing water with surface overflow. Final rinse compartment has influent grade A water maintained at 190 ±10°F. Work basket held 15 ±5 minutes in each compartment.

NOTE: Parts shall be free of water breaks after rinsing.

↓

Dry parts in a convective air current oven at 200 to 225°F for a minimum of 15 minutes.

↓

WATER PURITY

GRADES	A	B
Chlorine, maximum ppm	0.1	1.0
Conductivity, maximum microohm/cm	2.5	20
pH range	6.0 - 8.0	–
Visual Clarity	No turbidity, oil or sediment	

TABLE 7

BRAZE ALLOY QUALITY AFTER BRAZING CYCLE FOR ONE MODULE'S WORTH OF EACH – SEED, BLANKET AND REFLECTOR LWBR GRIDS

GRID SERIAL NUMBER	LONGITUDINAL CRACKS		BRAZE FLOW		BRAZE FILLET		BRAZE ALLOY BONDING	
	TOTAL CRACKS		INADEQUATE AND/OR ROUGH APPEARANCE		LACK AND/OR LACK OF SMOOTH FILLET		LACK OF VISUAL EVIDENCE OF BRAZE ALLOY IN ALL CURLS	LACK OF ALLOY IN CURLS OF EACH JOINT
	CRITICAL JOINTS	NON CRITICAL JOINTS	CRITICAL JOINTS	NON CRITICAL JOINTS	CRITICAL JOINTS	NON CRITICAL JOINTS		
SEED								
0101	21	47	0	0	5	8	0	0
0102	0	3	3	2	27	11	0	0
0103	9	38	1	6	6	23	0	0
0105	4	21	0	0	6	10	0	0
0106	18	35	3	14	10	12	0	0
0107	6	23	6	6	29	17	6	0
0109	23	44	0	2	23	11	0	0
0110	27	37	0	2	27	12	7	0
0111	1	0	0	0	2	0	6	0
0112	0	0	0	0	3	3	0	0
0113	4	4	4	3	7	11	0	0
0114	27	54	3	4	12	8	0	0
BLANKET								
1031	2	2	1	3	2	2	0	0
1032	1	6	3	0	1	1	0	0
1101	5	11	3	7	0	3	2	0
1102	2	6	1	1	0	0	4	0
1103	37	22	2	1	1	2	0	0
1104	7	6	3	6	2	1	0	0
1105	1	3	2	3	3	2	0	0
1107	2	3	4	3	3	4	2	0
REFLECTOR								
5031	10	27	6	5	1	5	0	0
5102	14	43	1	2	8	1	14	0
5103	16	62	5	6	1	20	0	0
5104	2	17	1	7	0	0	0	0
5105	7	38	1	0	0	2	0	0
5106	10	30	0	0	7	0	1	0

TABLE 8

BRAZE JOINT QUALITY ACCEPTANCE CRITERIA FOR LWBR GRIDS

GRID TYPE	NUMBER OF HINGE-PIN-CURL JOINTS	NUMBER OF HINGE-PIN-CURL CRITICAL JOINTS INSPECTED (100%)	NUMBER OF HINGE-PIN-CURL NON-CRITICAL JOINTS INSPECTED (SAMPLE) (1)	ALLOWABLE DEFECTS			
				LONGITUDINAL CRACKS, INADEQUATE AND/OR ROUGH APPEARANCE OF BRAZE FLOW, AND LACK OF SMOOTH FILLETS		LACK OF BRAZE ALLOY IN ALL CURLS	LACK OF ALLOY IN CURLS OF EACH JOINT (3)
				CRITICAL (2)	NON-CRITICAL		
SEED	9576	528	680	40	120	504	1/3
BLANKET I	6973	532	551	41	90	367	1/3
BLANKET II	8911	709	593	56	94	469	1/3
BLANKET III	9994	768	893	61	142	526	1/3
REFLECTOR IV	4047	209	984	42	168	213	1/3
REFLECTOR V	2888	202	328	35	55	152	1/3

NOTE: (1) NON-CRITICAL BRAZE QUALITY INSPECTION WAS REQUIRED FOR THE FIRST MODULE'S WORTH OF SEED, BLANKET TYPE I AND REFLECTOR TYPE V GRIDS.

(2) BRAZE CRACKS IN THE INSPECTED CURLS OF EACH CONNECTOR SHALL NOT EXCEED 50% OF THE NUMBER OF CURLS INSPECTED.

(3) TWO-THIRDS (2/3) OF THE CURLS ON ANY HINGE-PIN JOINT MUST SHOW EVIDENCE OF BRAZE ALLOY.

TABLE 9
METALLOGRAPHIC EVALUATION OF BRAZED JOINTS
LWBR SEED GRID S/N 0020

GRID & SECTION NO.	LONGITUDINAL			TRANSVERSE										
	75X VISUAL INSPECTION		500X VISUAL INSPECTION	75X VISUAL INSPECTION										500X VISUAL INSPECTION
	CRACKS	BOND LENGTH (1)	GAMMA PHASE	CIRCUMFERENTIAL CRACKS		BOND LENGTH (1) CLOSED CURL		BOND LENGTH (1) OPEN CURL		INTERNAL VOIDS	BASE METAL EROSION	BRAZE ALLOY PENETRATION	INTER-GRANULAR PENETRATION	GAMMA PHASE
				TOP CURL	BOTTOM CURL	TOP CURL	BOTTOM CURL	TOP CURL	BOTTOM CURL	ALL CURLS	ALL CURLS	ALL CURLS	ALL CURLS	
ACCEPTABLE LIMITS	LESS THAN LENGTH OF CURL (2)	GREATER THAN 60%	SEE FIGURE ___ FOR STANDARD (2)	NONE ALLOWED (2)		GREATER THAN 270°		GREATER THAN 150°		≤ 25% OF BOND LENGTH (2)	≤ 20% OF MATERIAL THICKNESS (2)	≤ 20% OF MATERIAL THICKNESS (2)	NONE ALLOWED (2)	SEE FIGURE ___ FOR STANDARD (2)
SHEET METAL-PIN CURL SECTION	9 CURLS PER JOINT	9 CURLS PER JOINT	5 CURLS PER JOINT											
1	A	OK	A	A	2 CRACKS	360°	360°	225°	230°	A	A	A	A	A
2	A	OK	A	A	A	325°	360°	230°	240°	A	A	A	A	A
3	A	OK	A	A	A	360°	360°	235°	250°	A	A	A	A	A
4	A	OK	A	A	A	360°	360°	245°	230°	A	A	A	A	A
5	1 JOINT CRACKED FULL LENGTH OF CURL	OK	A	A	A	360°	360°	225°	240°	A	A	A	A	A
6	A	OK	A	A	A	360°	330°	240°	240°	A	A	A	A	A
7	A	OK	A	ONE 0.070" CRACK	A	360°	360°	225°	240°	A	A	A	A	A
8	A	OK	A	A	A	360°	360°	215°	240°	A	A	A	A	A
9	A	OK	A	A	ONE CRACK	325°	360°	225°	240°	A	A	A	A	A
10	A	OK	A	A	A	360°	360°	230°	245°	A	A	A	A	A
11	1 JOINT CRACKED FULL LENGTH OF CURL	OK	A	A	A	360°	360°	225°	230°	A	A	A	A	A
12	A	OK	A	A	A	325°	360°	220°	230°	A	A	A	A	A
CONNECTOR CURL-PIN JOINTS				8 CLOSED CURLS PER JOINT TOP	3 CLOSED CURLS PER JOINT BOTTOM	8 CLOSED CURLS PER JOINT TOP	8 CLOSED CURLS PER JOINT BOTTOM							
1	A	OK	A	–	A	–	OK	–	–	A	A	A	A	A
2	A	OK	A	–	ONE .005" CRACK	–	OK	–	–	A	A	A	A	A
3	A	OK	A	ONE 0.013" CRACK	–	OK	–	–	–	A	A	A	A	A
4	A	OK	A	A	–	OK	–	–	–	A	A	A	A	A

(1) OK MEANS BOND LENGTH WAS LESS THAN 100% BUT GREATER THAN MINIMUM ACCEPTABLE LIMITS
(2) A MEANS ATTRIBUTES ARE WITHIN ACCEPTABLE LIMITS

TABLE 10
METALLOGRAPHIC EVALUATION OF BRAZED JOINTS
LWBR BLANKET GRID TYPE III (REM-3)

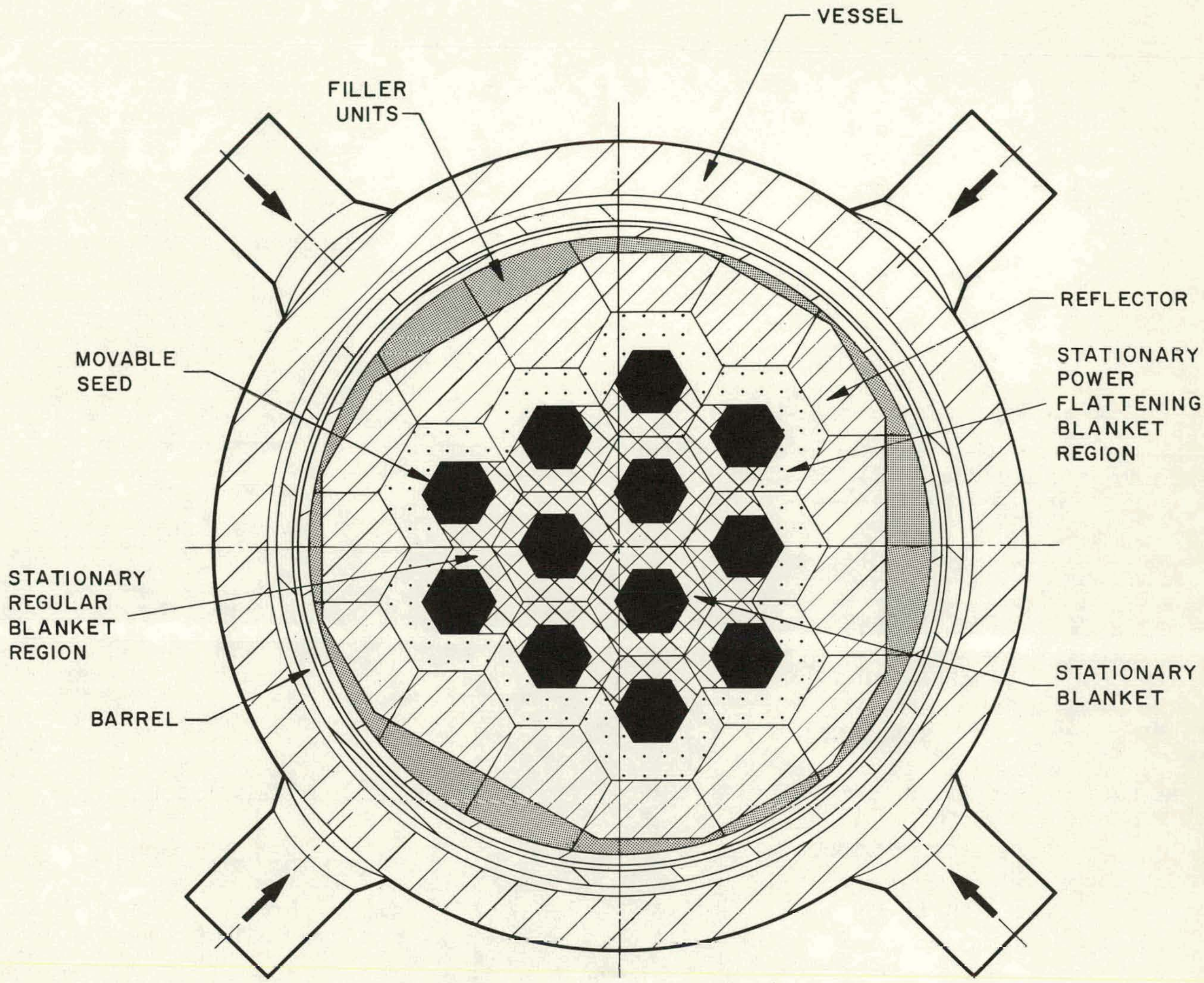
GRID & SECTION NO.	LONGITUDINAL			TRANSVERSE										
	75X VISUAL INSPECTION		500X VISUAL INSPECTION	75X VISUAL INSPECTION										500X VISUAL INSPECTION
	CRACKS	BOND LENGTH (1)	GAMMA PHASE	CIRCUMFERENTIAL CRACKS		BOND LENGTH (1)				INTERNAL VOIDS	BASE METAL EROSION	BRAZE ALLOY PENETRATION	INTER-GRANULAR PENETRATION	GAMMA PHASE
						CLOSED CURL		OPEN CURL						
				TOP CURL	BOTTOM CURL	TOP CURL	BOTTOM CURL	TOP CURL	BOTTOM CURL	ALL CURLS	ALL CURLS	ALL CURLS	ALL CURLS	
ACCEPTABLE LIMITS	LESS THAN LENGTH OF CURL (2)	GREATER THAN 80%	SEE FIGURE ___ FOR STANDARD (2)	NONE ALLOWED (2)		GREATER THAN 270°		GREATER THAN 150°		≤25% OF BOND LENGTH (2)	≤20% OF MATERIAL THICKNESS (2)	≤20% OF MATERIAL THICKNESS (2)	NONE ALLOWED (2)	SEE FIGURE ___ FOR STANDARD (2)
SHEET METAL-PIN CURL SECTION	9 CURLS PER JOINT	9 CURLS PER JOINT	9 CURLS PER JOINT											
1	A	OK	A	A	A	360°	360°	220°	220°	A	A	A	A	A
2	A	OK	A	A	A	340°	360°	215°	215°	A	A	A	A	A
3	A	OK	A	A	A	360°	360°	215°	230°	A	A	A	A	A
4	A	OK	A	A	A	360°	360°	215°	225°	A	A	A	A	A
5	A	OK	A	A	A	360°	360°	220°	225°	A	A	A	A	A
6	A	OK	A	A	ONE CRACK	315°	360°	245°	252°	A	A	A	A	A
7	A	OK	A	A	A	320°	360°	245°	242°	A	A	A	A	A
8	JOINT DESTROYED DURING SECTIONING			A	A	320°	310°	235°	233°	A	A	A	A	A
9	A	OK	A	A	A	360°	360°	235°	250°	A	A	A	A	A
10	A	OK	A	A	A	330°	360°	195°	213°	A	A	A	A	A
11	A	OK	A	A	A	360°	360°	210°	215°	A	A	A	A	A
12	A	OK	A	A	A	360°	360°	220°	217°	A	A	A	A	A
CONNECTOR CURL-PIN JOINTS				6 TOP CLOSED CURLS PER JOINT	6 BOTTOM CLOSED CURLS PER JOINT	6 TOP CLOSED CURLS PER JOINT	6 BOTTOM CLOSED CURLS PER JOINT							
1	A	100%	A	–	A	–	360°	–	–	A	A	A	A	A
2	A	100%	A	–	A	–	360°	–	–	A	A	A	A	A
3	A	100%	A	A	–	360°	–	–	–	A	A	A	A	A
4	A	100%	A	A	–	360°	–	–	–	A	A	A	A	A

(1) OK MEANS BOND LENGTH WAS LESS THAN 100% BUT GREATER THAN MINIMUM ACCEPTABLE LIMITS
(2) A MEANS ATTRIBUTES ARE WITHIN ACCEPTABLE LIMITS

TABLE II
METALLOGRAPHIC EVALUATION OF BRAZED JOINTS
LWBR REFLECTOR GRID S/N 5014

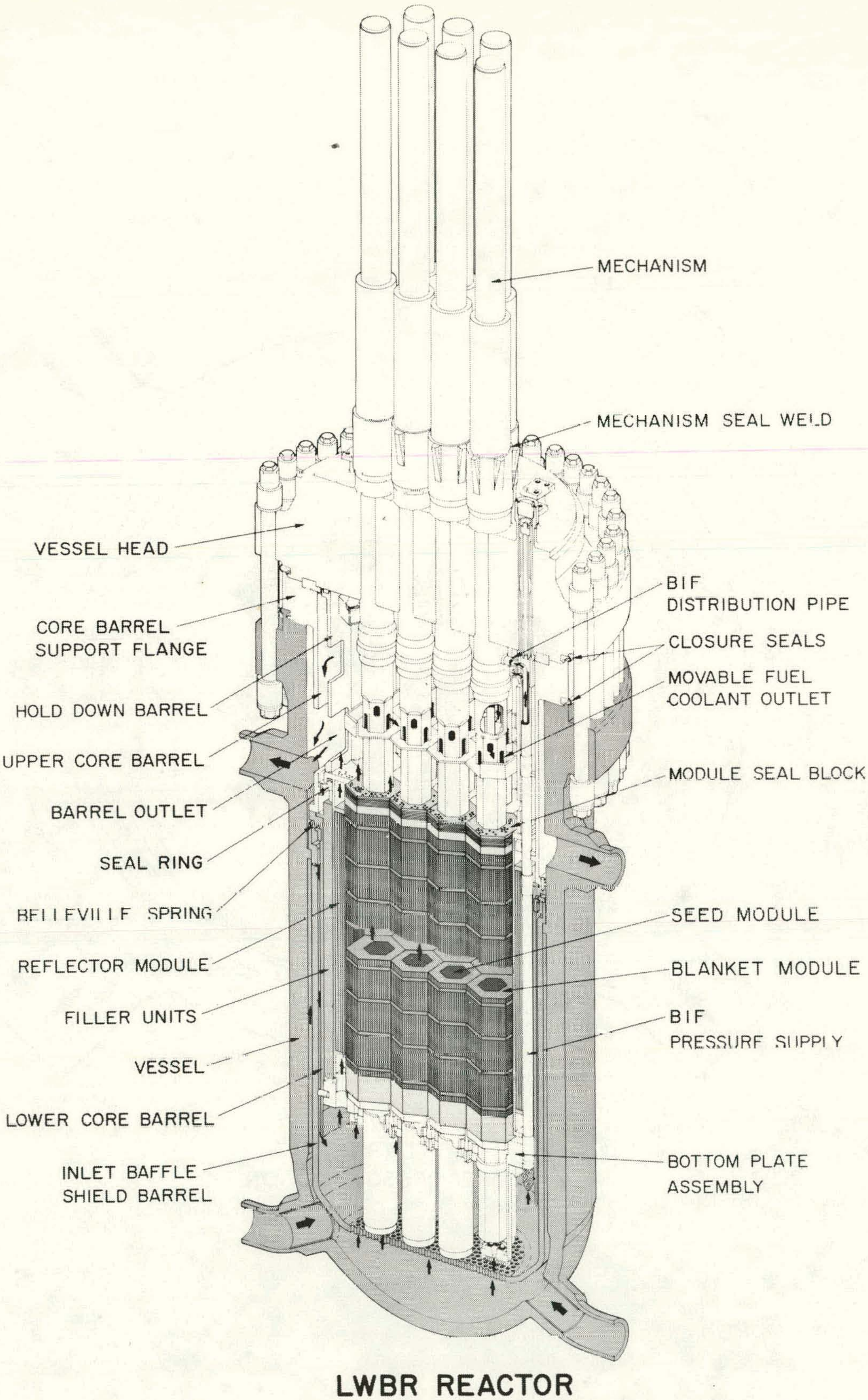
GRID & SECTION NO.	LONGITUDINAL			TRANSVERSE										
	75X VISUAL INSPECTION		500X VISUAL INSPECTION	75X VISUAL INSPECTION										500X VISUAL INSPECTION
	CRACKS	BOND LENGTH (1)	GAMMA PHASE	CIRCUMFERENTIAL CRACKS		BOND LENGTH (1)				INTERNAL VOIDS	BASE METAL EROSION	BRAZE ALLOY PENETRATION	INTER-GRANULAR PENETRATION	GAMMA PHASE
						CLOSED CURL		OPEN CURL						
				TOP CURL	BOTTOM CURL	TOP CURL	BOTTOM CURL	TOP CURL	BOTTOM CURL	ALL CURLS	ALL CURLS	ALL CURLS	ALL CURLS	
ACCEPTABLE LIMITS	LESS THAN LENGTH OF CURL (3)	GREATER THAN 80%	SEE FIGURE ___ FOR STANDARD (3)	NONE ALLOWED (3)		GREATER THAN 270°		GREATER THAN 150°		≤25% OF BOND LENGTH (3)	≤20% OF MATERIAL THICKNESS (3)	≤20% OF MATERIAL THICKNESS (3)	NONE ALLOWED (3)	SEE FIGURE ___ FOR STANDARD (3)
SHEET METAL PIN CURL SECTION	9 CURLS PER JOINT	9 CURLS PER JOINT	9 CURLS PER JOINT											
1	A	OK	A	A	A	(2)	360°	230°	240°	A	A	A	A	A
2	A	OK	A	A	A	360°	360°	225°	255°	A	A	A	A	A
3	A	OK	A	ONE CRACK 0.063"	A	360°	340°	210°	220°	A	A	A	A	A
4	A	OK	A	A	A	240°	360°	225°	225°	A	A	A	A	A
5	A	ONE OF 9 CURLS HAD 40% BOND	A	ONE CRACK 0.042"	A	285°	330°	215°	215°	A	A	A	A	A
6	A	OK	A	A	A	315°	(2)	210°	215°	A	A	A	A	A
7	A	OK	A	A	A	320°	(2)	210°	220°	A	A	A	A	A
8	A	OK	A	ONE CRACK 0.044"	A	310°	360°	210°	220°	A	A	A	A	A
9	A	OK	A	A	A	315°	360°	225°	230°	A	A	A	A	A
10	A	OK	A	A	A	310°	360°	210°	225°	A	A	A	A	A
11	A	OK	A	A	A	285°	360°	210°	230°	A	A	A	A	A
12	A	ONE OF 9 CURLS HAD 40% BOND	A	A	A	360°	360°	225°	245°	A	A	A	A	A
CONNECTOR CURL-PIN JOINTS				7 TOP CLOSED CURLS PER JOINT	7 BOTTOM CLOSED CURLS PER JOINT	7 TOP CLOSED CURLS PER JOINT	7 BOTTOM CLOSED CURLS PER JOINT							
1	A	>80%	A	—	A	—	1 CURL – 0° 6 CURLS – 360°	—	—	A	A	A	A	A
2	A	100%	A	—	A	—	OK	—	—	A	A	A	A	A
3	ONE CRACK LESS THAN LENGTH OF CURL	>80%	A	A	—	OK	—	—	—	A	A	A	A	A
4	A	>80%	A	A	—	OK	—	—	—	A	A	A	A	A

(1) OK MEANS BOND LENGTH WAS LESS THAN 100% BUT GREATER THAN MINIMUM ACCEPTABLE LIMITS
(2) CURLS DESTROYED DURING SECTIONING
(3) A MEANS ATTRIBUTES ARE WITHIN ACCEPTABLE LIMITS



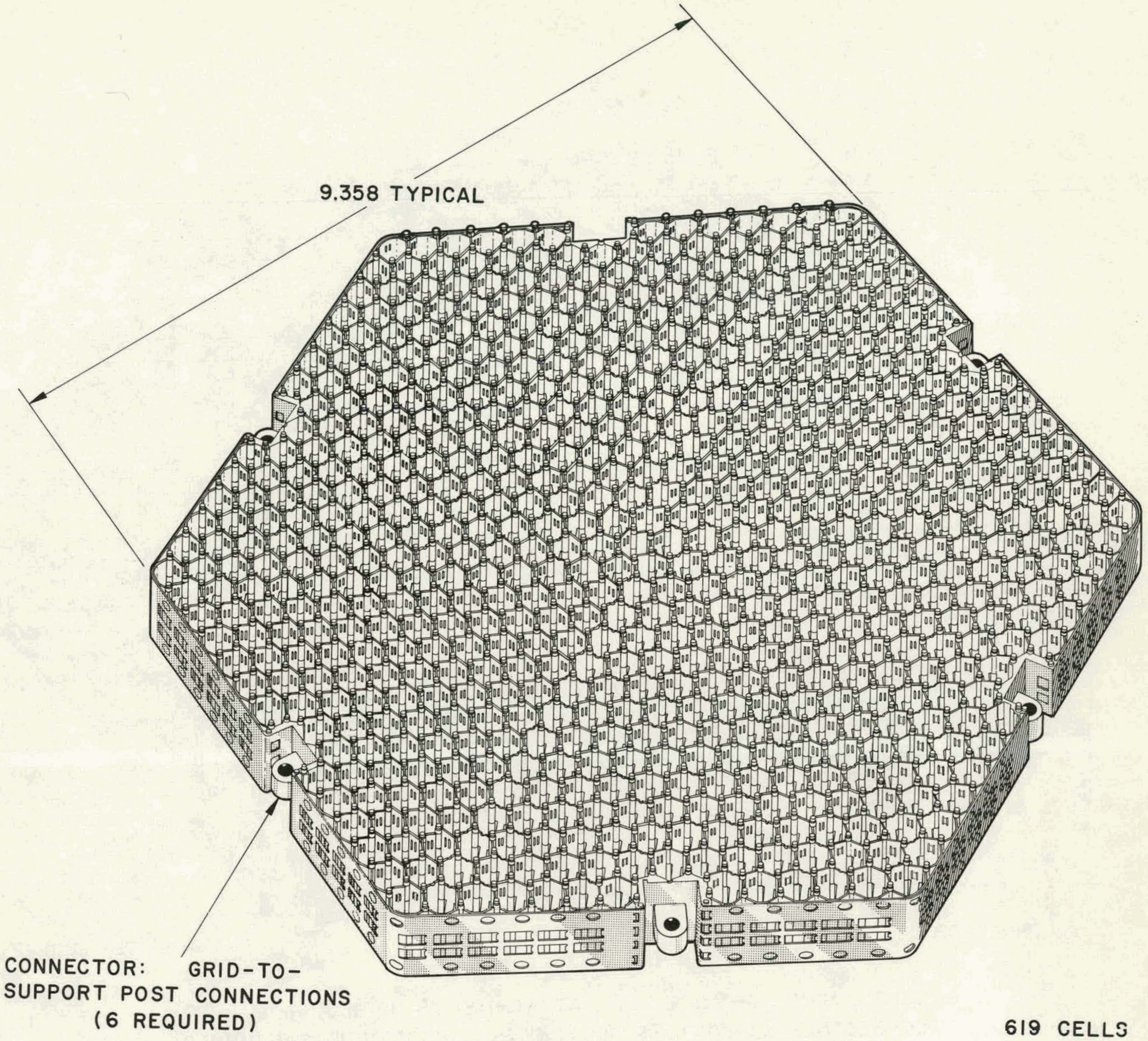
LWBR
CORE CROSS SECTION

Figure 1



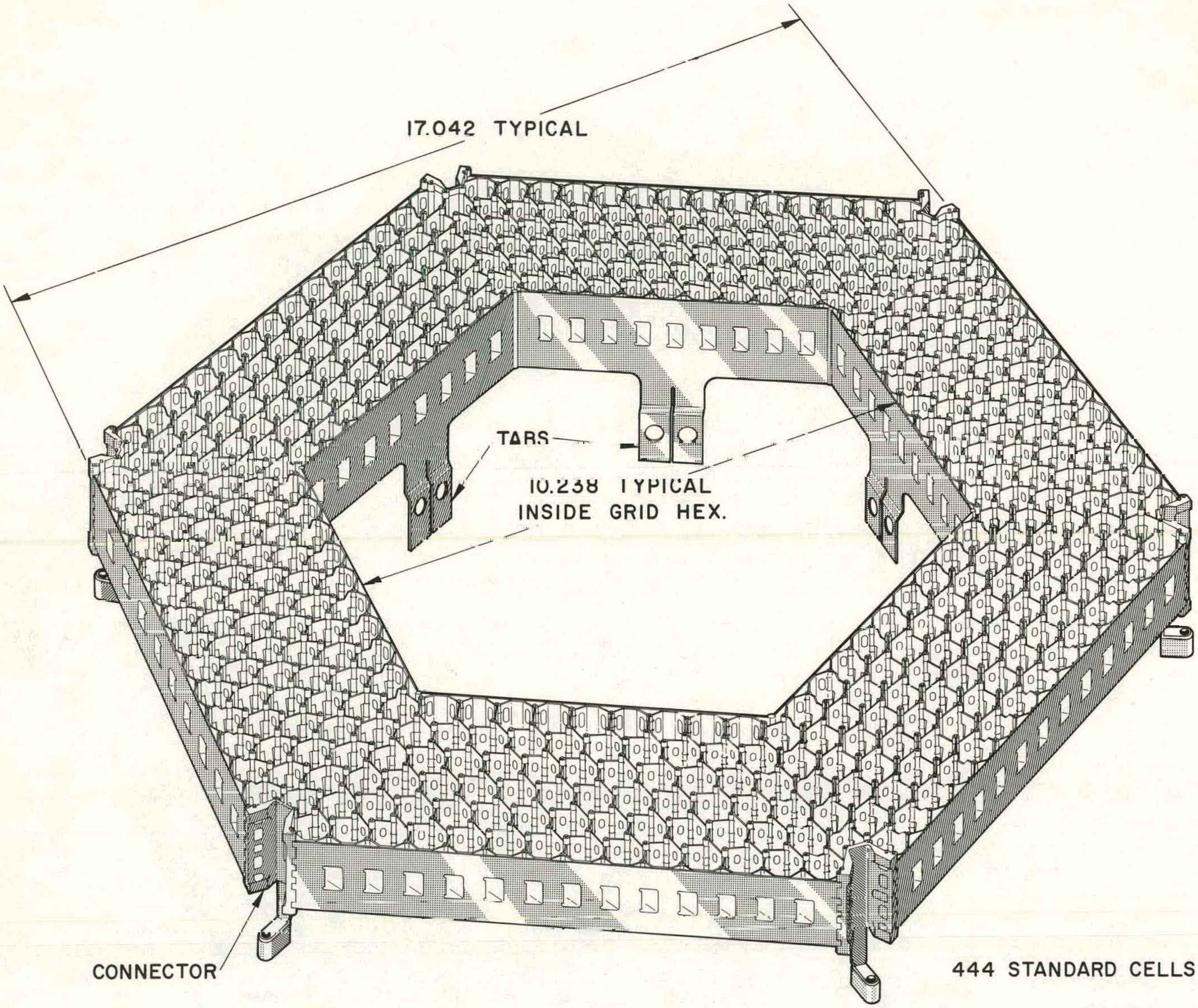
LWBR REACTOR

Figure 2



LWBR
SEED ROD
SUPPORT GRID

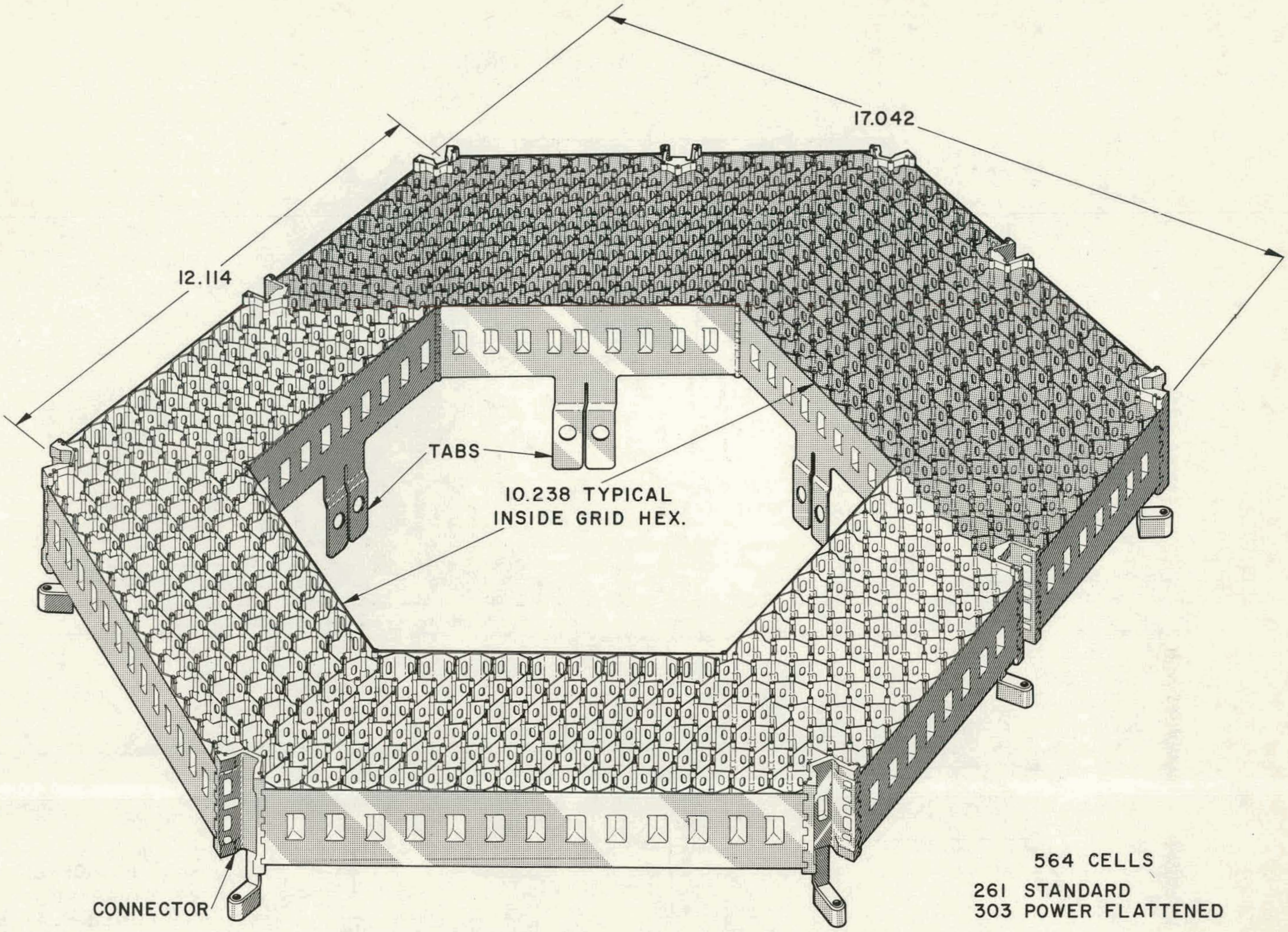
Figure 3



TABS: GRID-TO-GUIDE TUBE ATTACHMENTS (12 REQUIRED)
CONNECTORS: GRID-TO-SUPPORT POST CONNECTIONS (6 REQUIRED)

LWBR
BLANKET TYPE I
ROD SUPPORT GRID

Figure 4

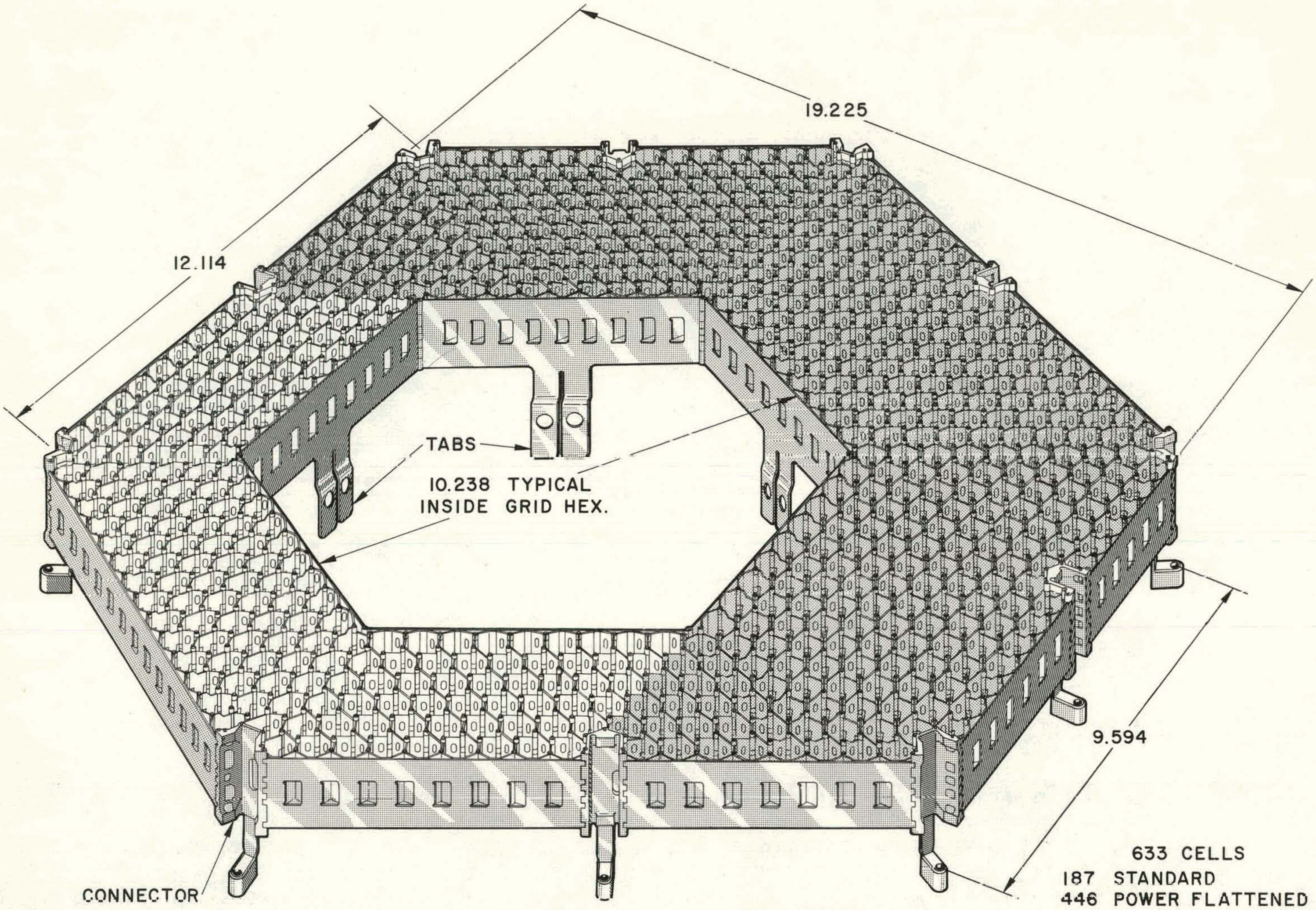


TABS: GRID-TO-GUIDE TUBE ATTACHMENTS (12 REQUIRED)
CONNECTORS: GRID-TO-SUPPORT POST CORNER CONNECTIONS (6 REQUIRED)
GRID-TO-SUPPORT POST SIDE CONNECTIONS (4 REQUIRED)

LWBR
BLANKET TYPE II
ROD SUPPORT GRID

STANDARD CELLS
POWER FLATTENING CELLS

Figure 5



TABS: GRID-TO-GUIDE TUBE ATTACHMENTS (12 REQUIRED)

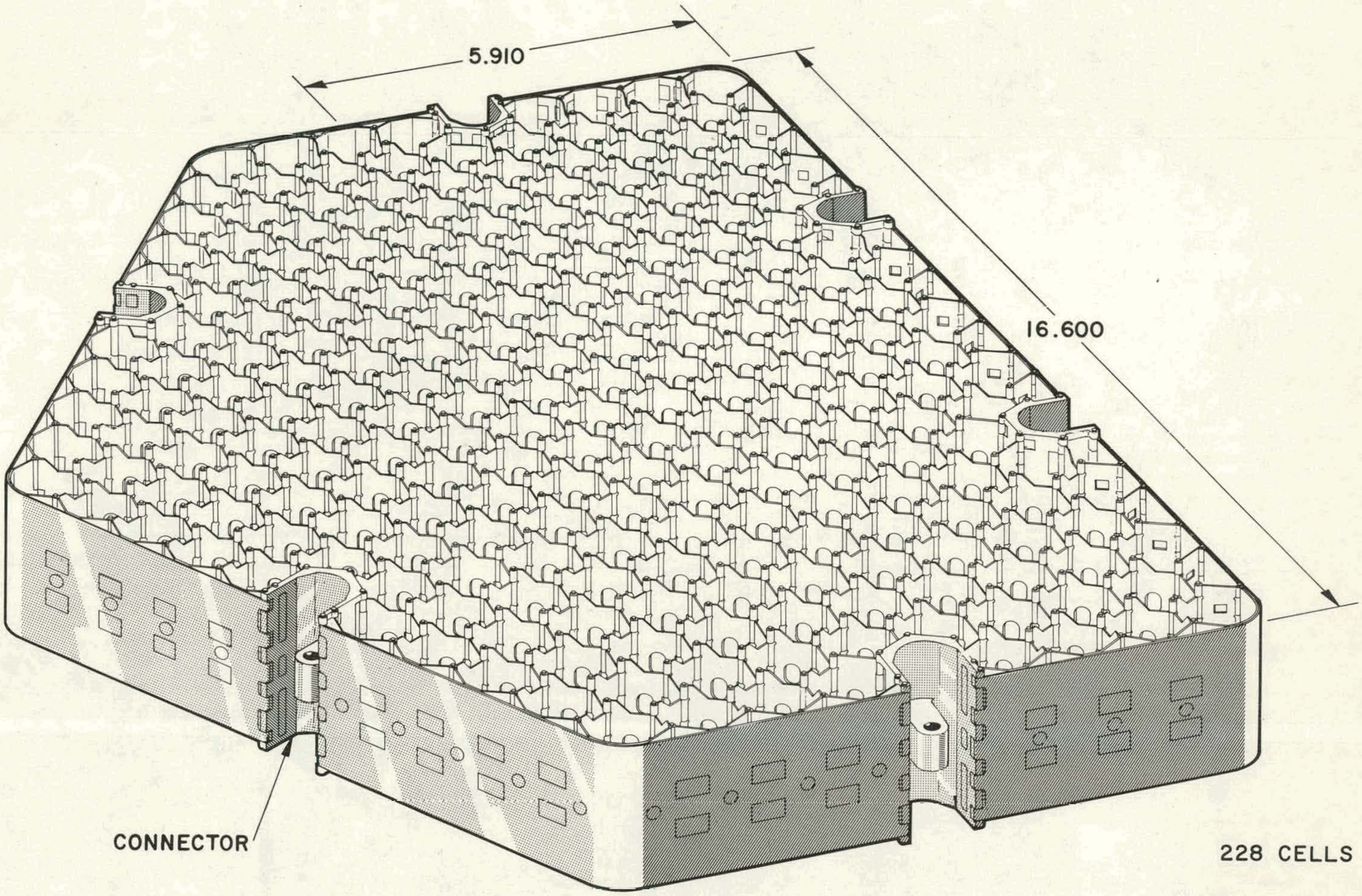
CONNECTORS: GRID TO SUPPORT POST CORNER CONNECTIONS (6 REQUIRED)
GRID-TO-SUPPORT POST SIDE CONNECTIONS (5 REQUIRED)

LWBR
BLANKET TYPE III
ROD SUPPORT GRID

STANDARD CELLS

POWER FLATTENING CELLS

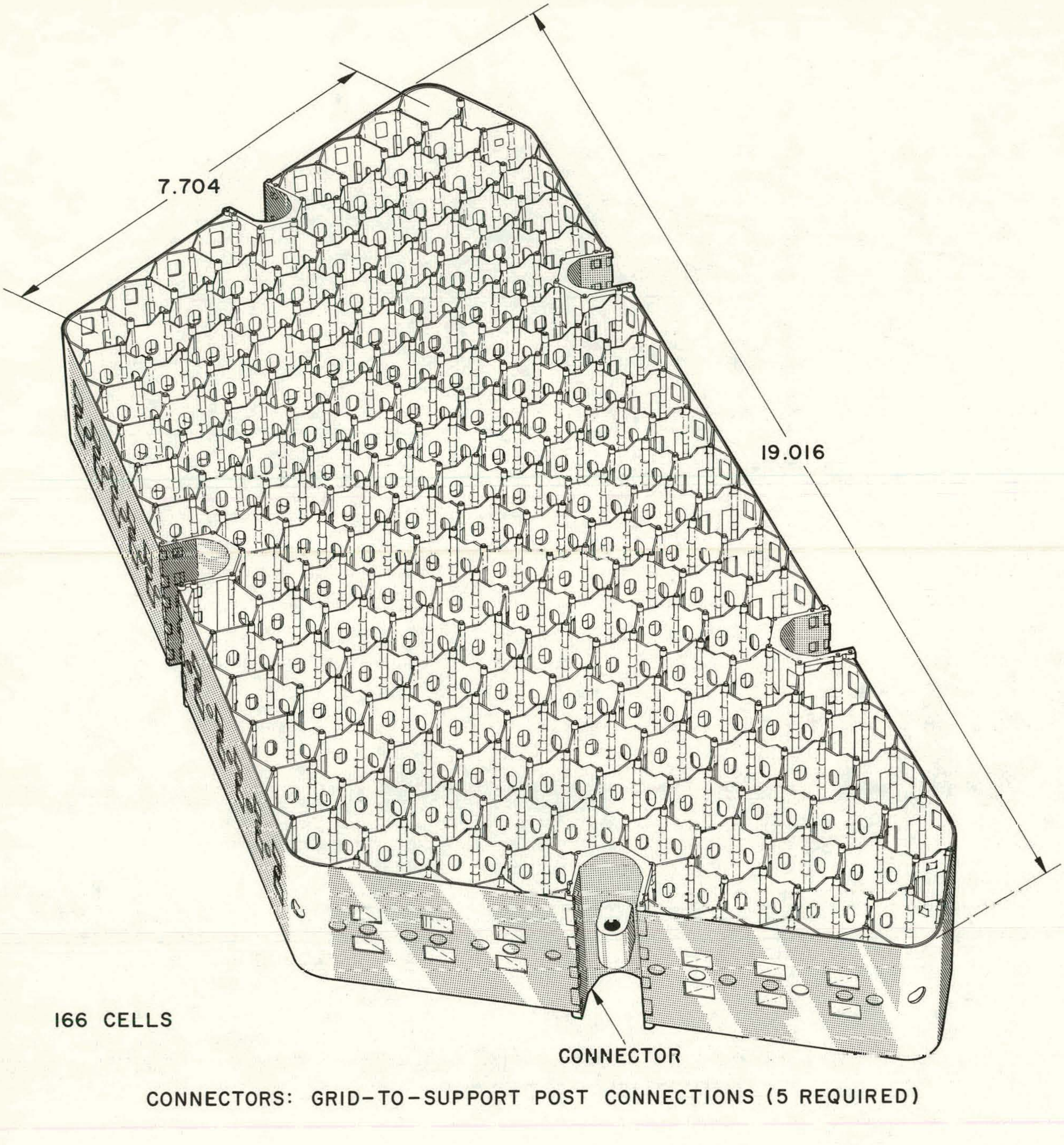
Figure 6



CONNECTORS: GRID-TO-SUPPORT POST CONNECTIONS (6 REQUIRED)

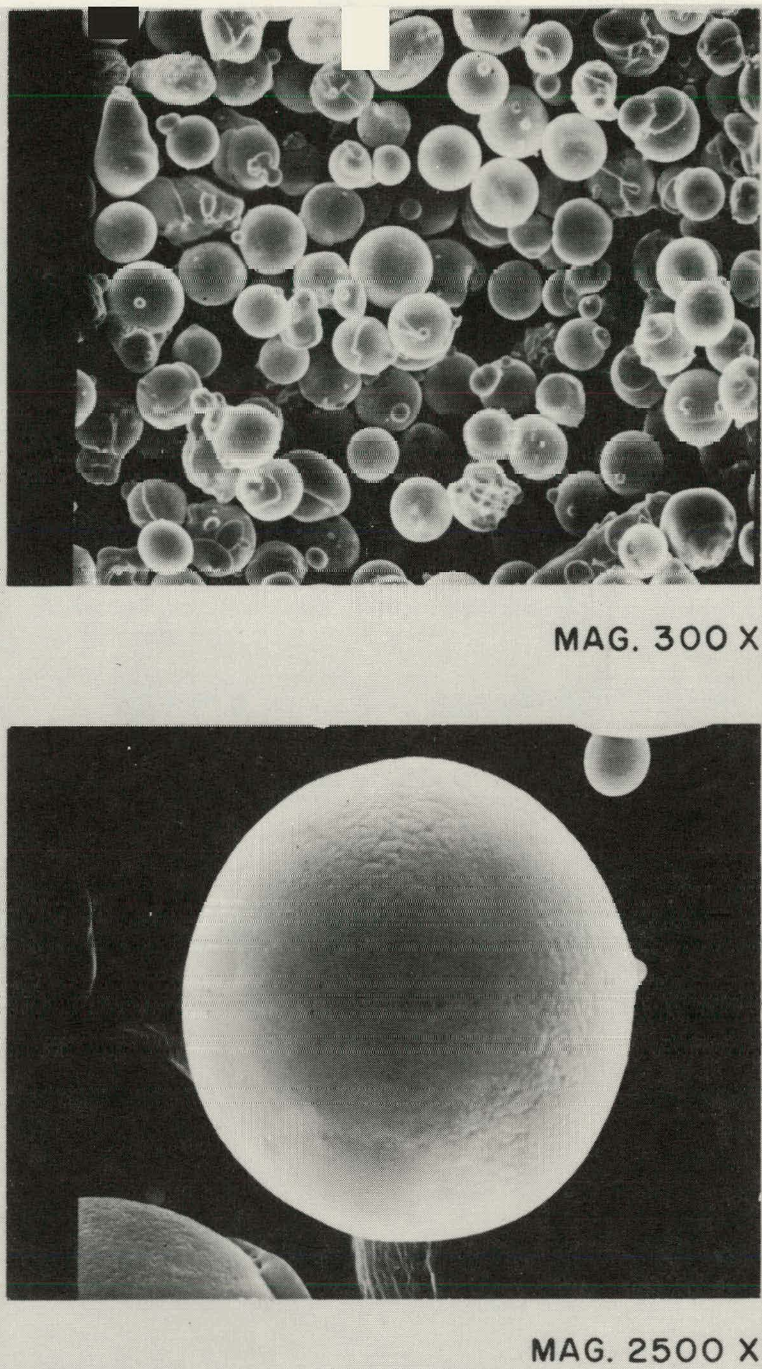
LWBR
REFLECTOR TYPE IV
ROD SUPPORT GRID

Figure 7



LWBR
REFLECTOR TYPE V
ROD SUPPORT GRID

Figure 8



NICKEL BASE-30 CHROMIUM-10 SILICON
BRAZE ALLOY POWDER

Figure 9

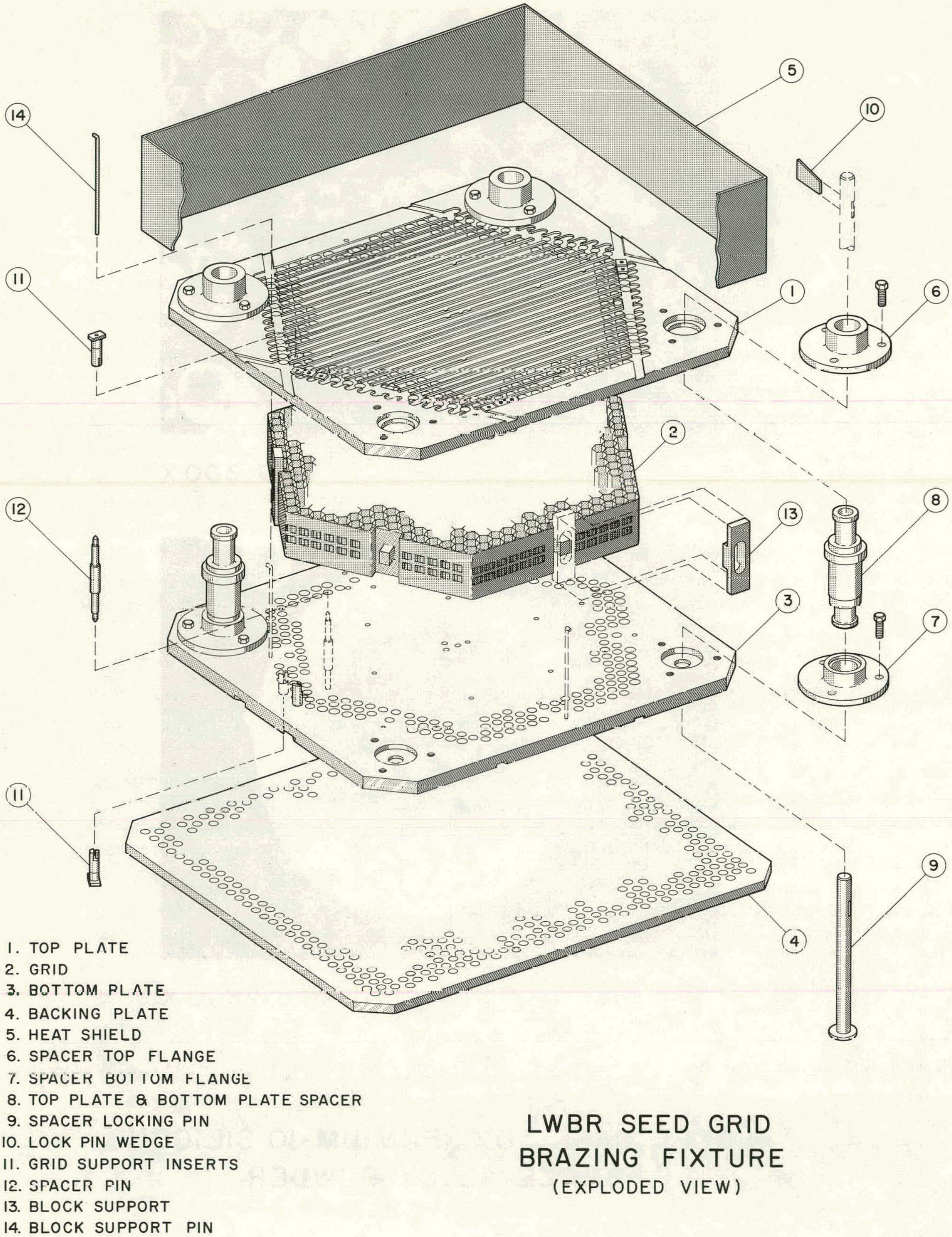
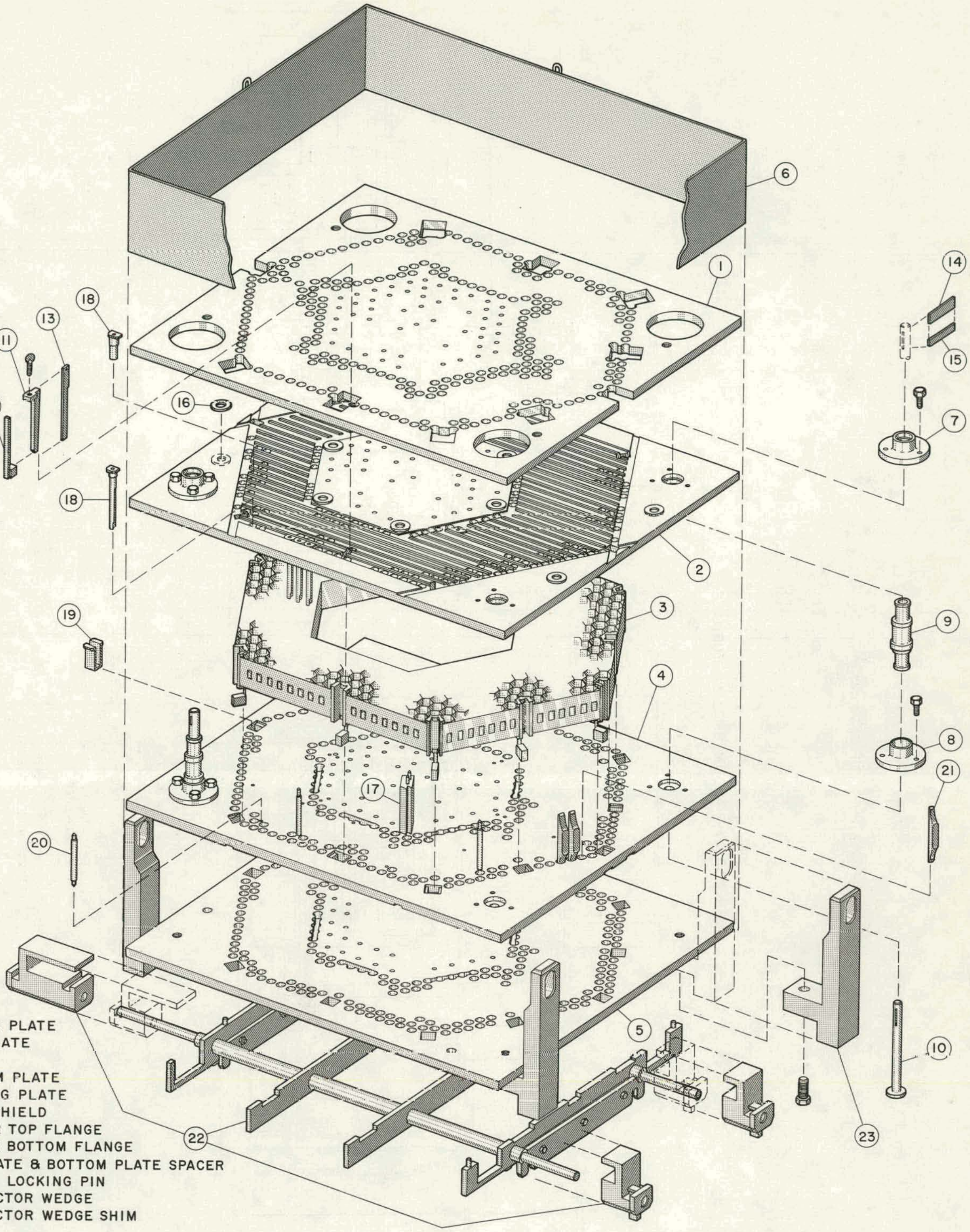

1. TOP PLATE
2. GRID
3. BOTTOM PLATE
4. BACKING PLATE
5. HEAT SHIELD
6. SPACER TOP FLANGE
7. SPACER BOTTOM FLANGE
8. TOP PLATE & BOTTOM PLATE SPACER
9. SPACER LOCKING PIN
10. LOCK PIN WEDGE
11. GRID SUPPORT INSERTS
12. SPACER PIN
13. BLOCK SUPPORT
14. BLOCK SUPPORT PIN
LWBR SEED GRID
BRAZING FIXTURE
(EXPLODED VIEW)

Figure 10

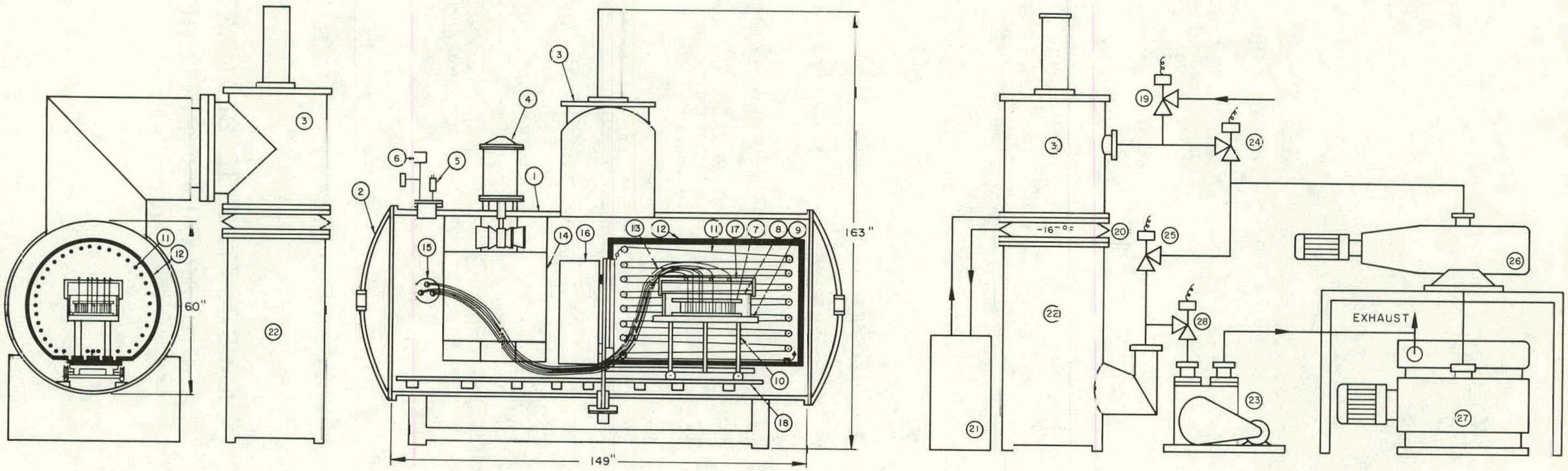


1. BAFFLE PLATE
2. TOP PLATE
3. GRID
4. BOTTOM PLATE
5. BACKING PLATE
6. HEAT SHIELD
7. SPACER TOP FLANGE
8. SPACER BOTTOM FLANGE
9. TOP PLATE & BOTTOM PLATE SPACER
10. SPACER LOCKING PIN
11. CONNECTOR WEDGE
12. CONNECTOR WEDGE SHIM
13. WEDGE
14. LOCK PIN WEDGE
15. LOCK PIN SHIM
16. SPACER WASHER
17. GRID CORNER INSERT BLOCK & PINS
18. GRID SUPPORT INSERTS
19. CONNECTOR FOOT SUPPORT INSERT
20. SPACER PIN
21. SLAT INSERT
22. BRAZING FIXTURE SUPPORT
23. BRAZING FIXTURE LIFTING BRACKET

LWBR TYPE II BLANKET
GRID BRAZING FIXTURE
(EXPLODED VIEW)

Figure 11

LWBR 250 KW VACUUM BRAZING FURNACE



LEGEND

1 CRES COLD WALL FURNACE CHAMBER
2 FURNACE DOOR
3 32" ANGLE VALVE
4 ATMOSPHERE COOLING FAN
5 IONIZATION GAGE
6 THERMOCOUPLE VACUUM GAGE
7 LWBR FIXTURED GRID
8 HEAT SHIELD
9 MOLYBDENUM LOAD HEARTH
10 WORK CART
11 MOLYBDENUM CABLE HEATING ELEMENT
12 MOLYBDENUM REFLECTOR SHIELDS
13 6 "K" TYPE THERMOCOUPLES
14 ATMOSPHERE BAFFLE
15 THERMOCOUPLE FEED THRU
16 INNER DOOR
17 THERMOCOUPLE HARNESS
18 CART TRACK
19 ARGON BACKFILL VALVE
20 COLD BAFFLE
21 REFRIG. - 170°F
22 DIFFUSION PUMP 33,000 LITERS/SEC
23 MECHANICAL HOLDING PUMP 30 M^3/HR
24 VALVE
25 VALVE
26 ROOTS TYPE BLOWER, 685 CFM
27 SINGLE STAGE MECHANICAL ROUGHING PUMP 162 CFM
28 VALVE

Figure 12

LWBR BRAZING FURNACE VACUUM SYSTEM
OPERATING CHARACTERISTICS

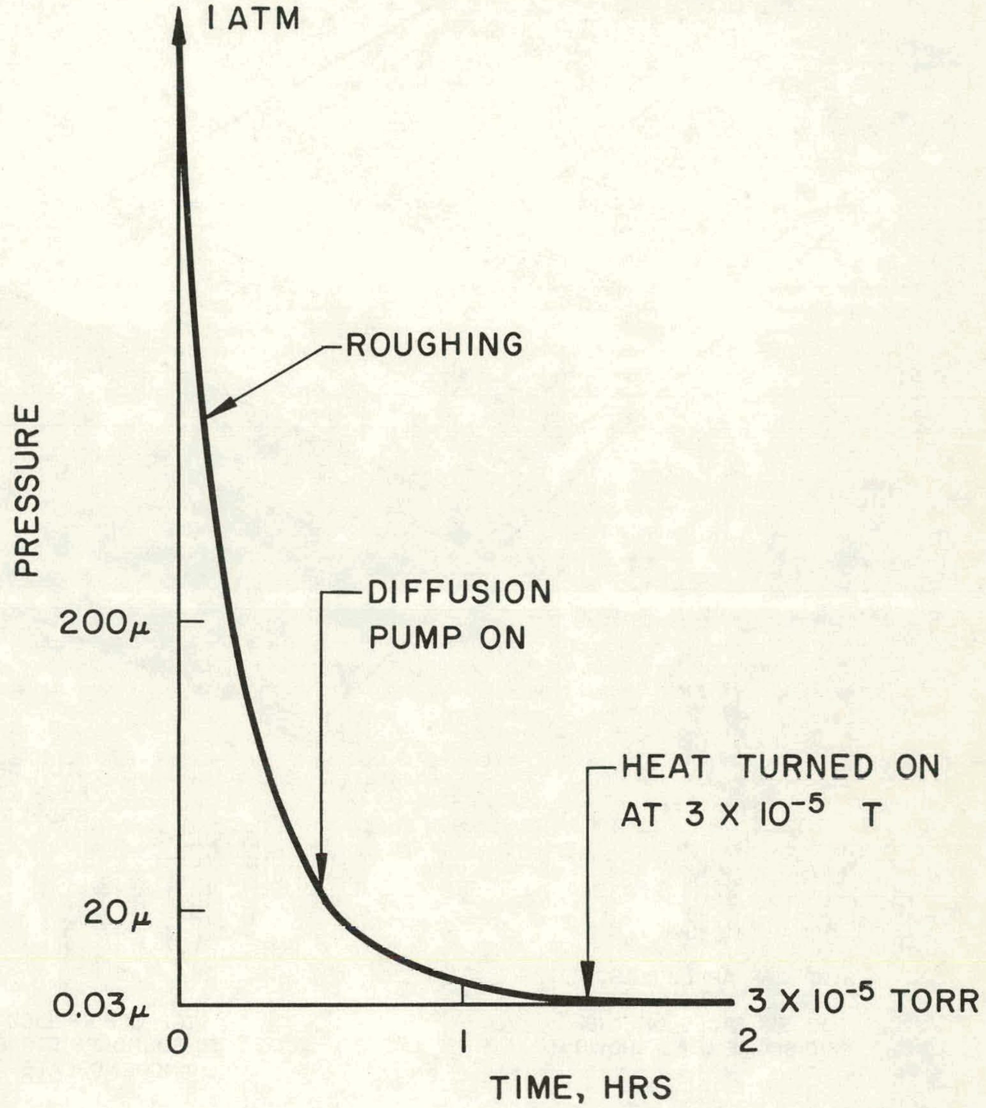
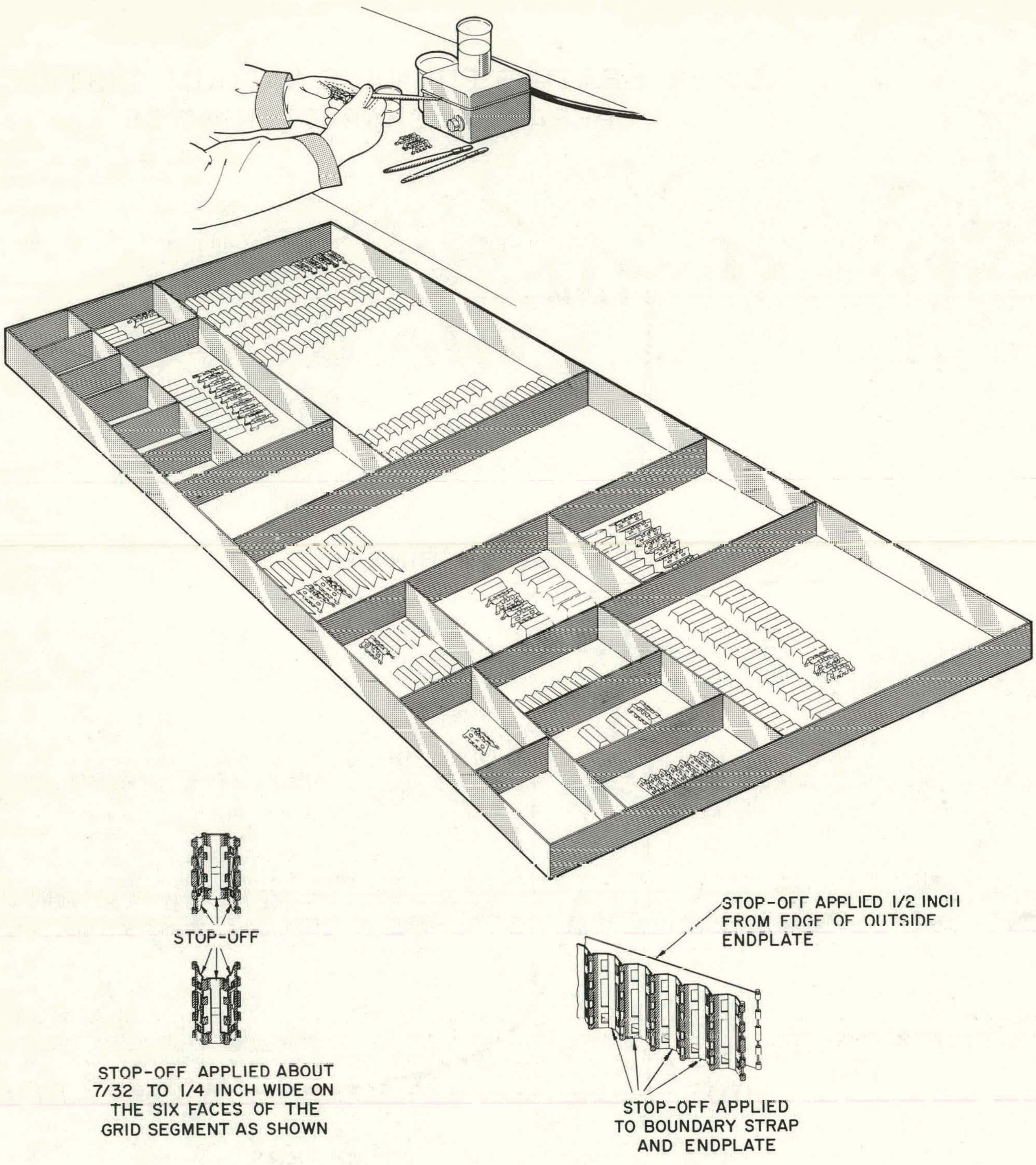
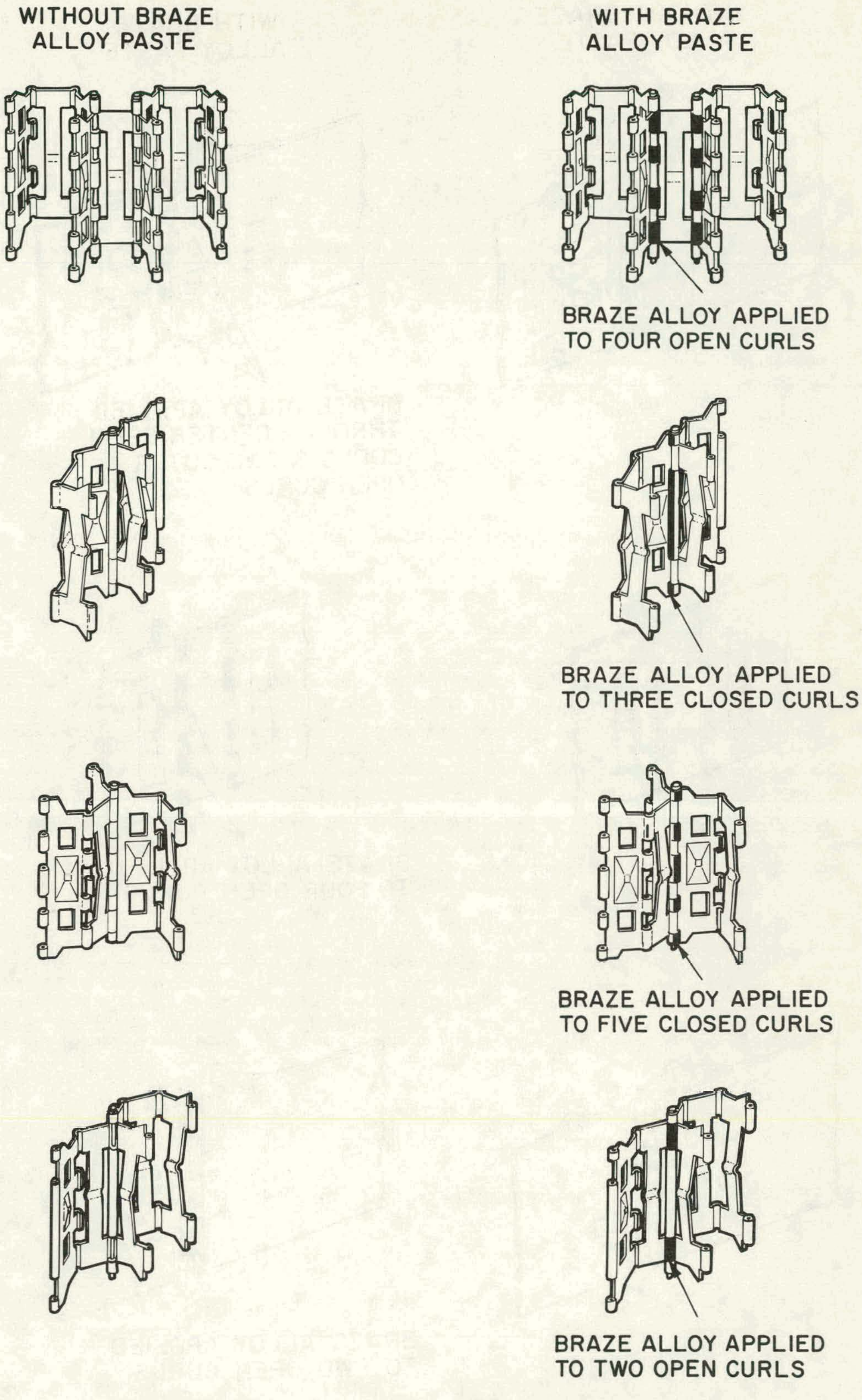


Figure 13



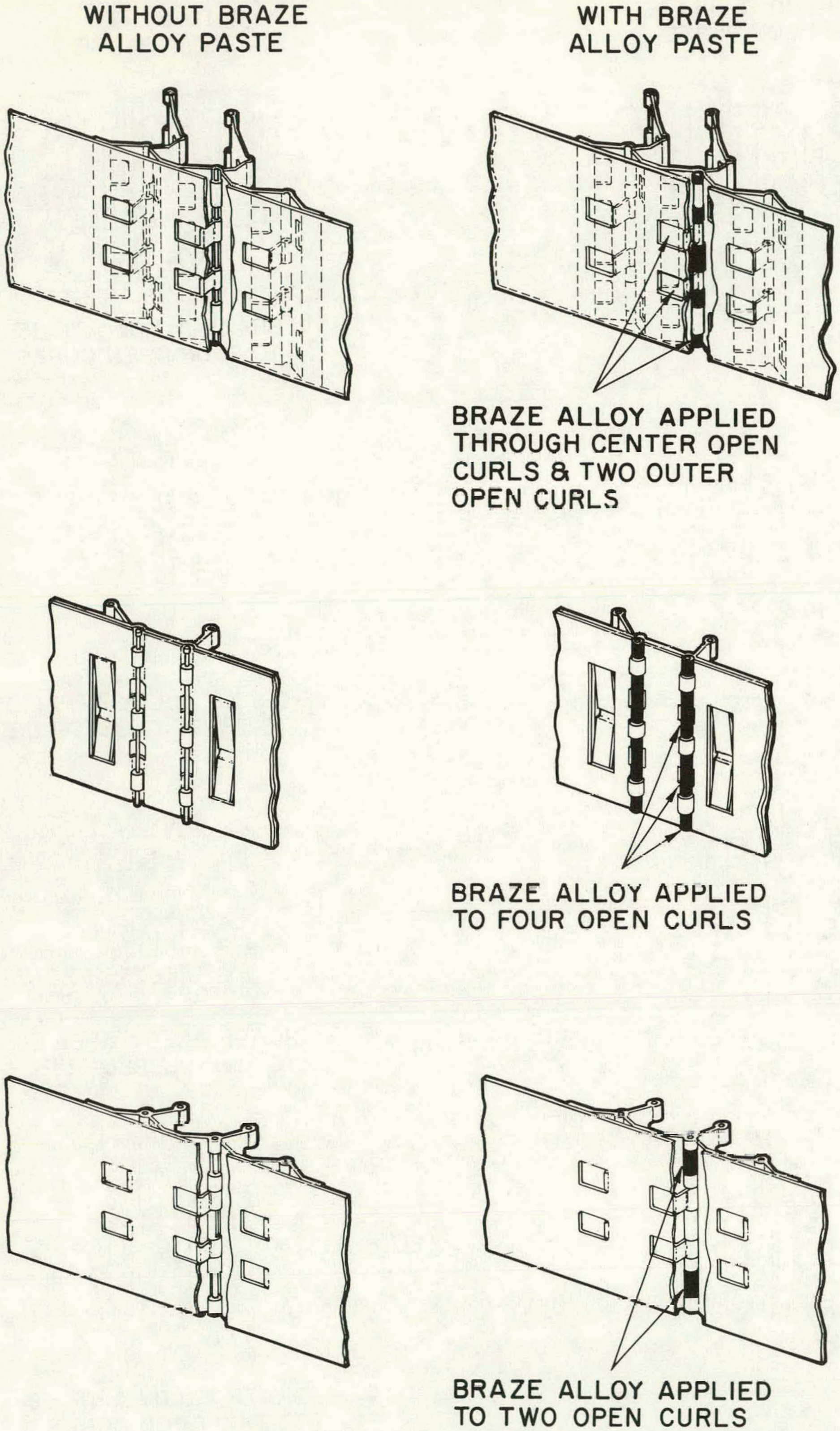
STOP-OFF APPLICATION ON LWBR GRID COMPONENTS

Figure 14



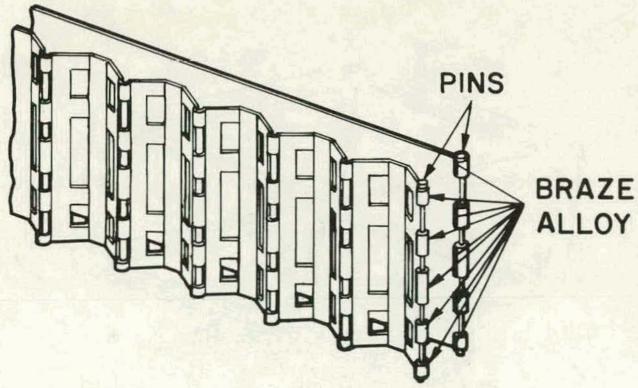
BRAZE ALLOY APPLICATION
ON LWBR GRID
INTERNAL SEGMENT JOINTS

Figure 15



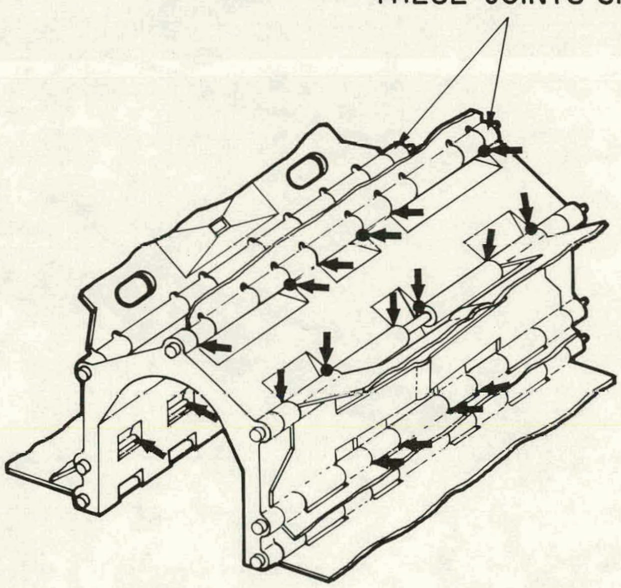
BRAZE ALLOY APPLICATION
ON LWBR GRID
EXTERNAL SEGMENT JOINTS

Figure 16



BRAZE ALLOY APPLIED TO FIVE CLOSED CURLS ON BOUNDRY STRAP AT EACH END AND TO THE CLOSED CURLS OF THE END PLATE AT EACH END WHILE PINS ARE TEMPORARILY INSERTED

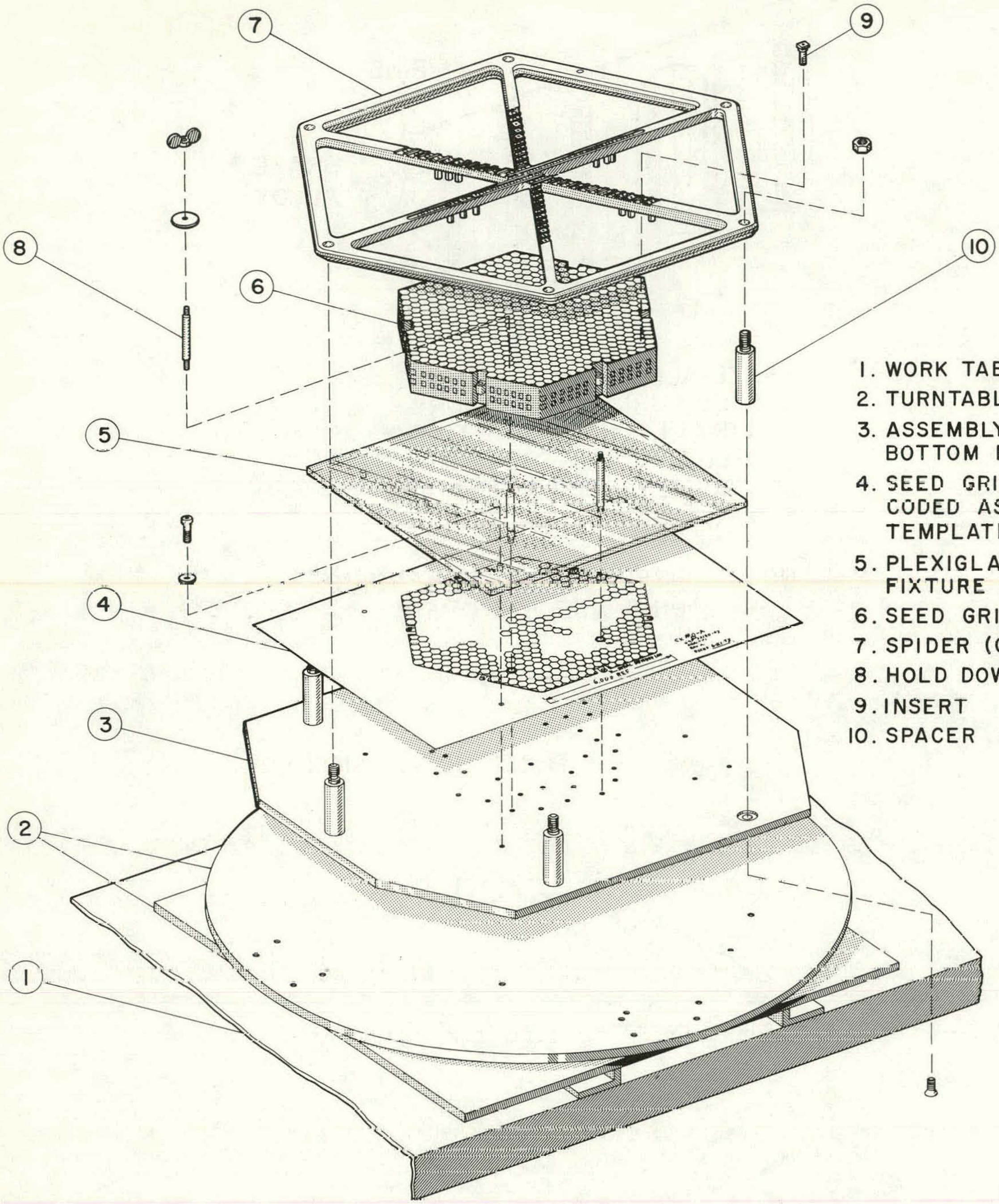
NOTE: BEFORE ALLOY HARDENS PINS ARE REMOVED



BRAZE ALLOY APPLIED TO THE TOP AND BOTTOM AREAS OF ALL CONNECTOR CURLS AS SHOWN ABOVE.

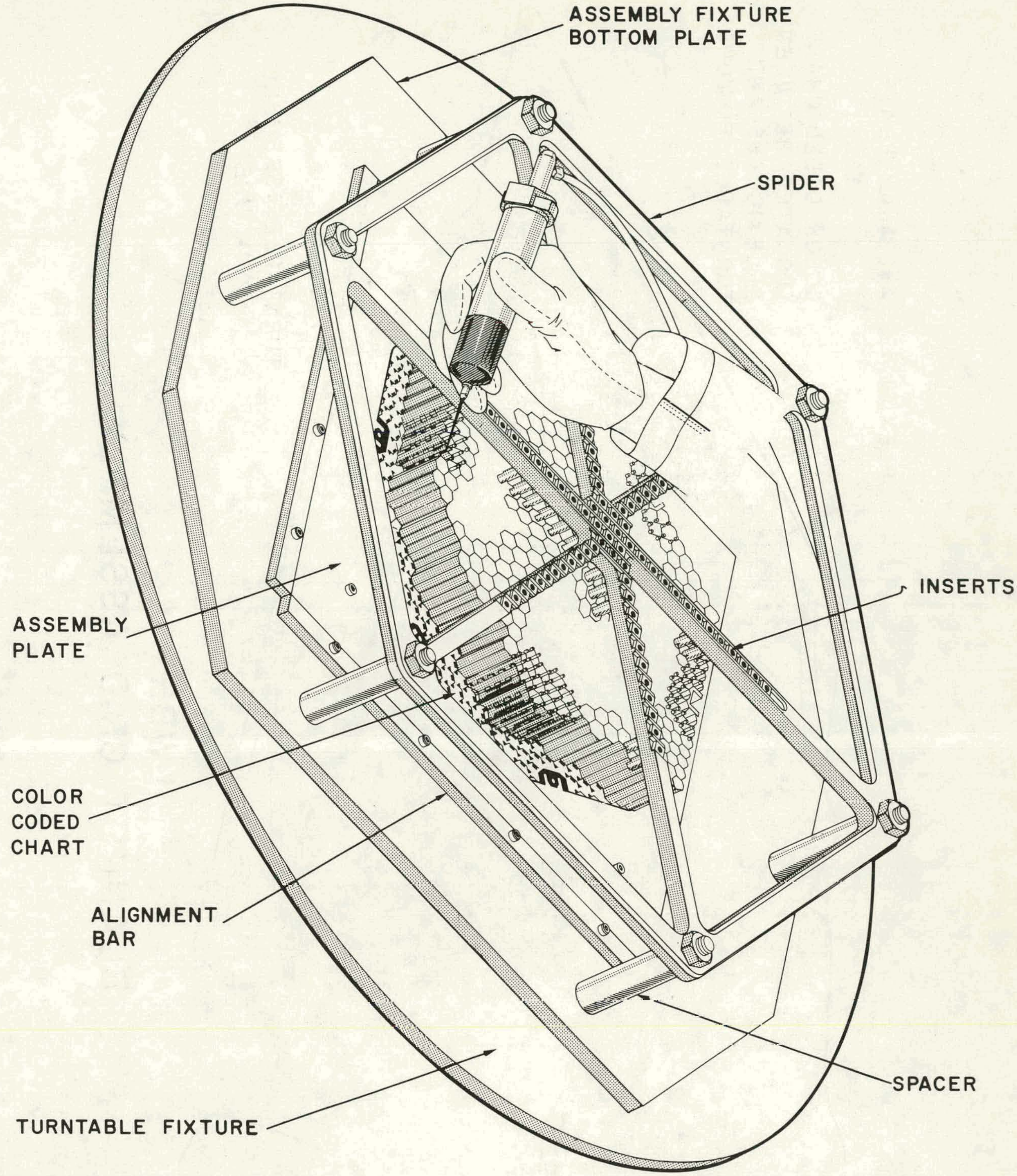
BRAZE ALLOY APPLICATION ON LWBR GRID END PLATES AND CONNECTOR JOINTS

Figure 17



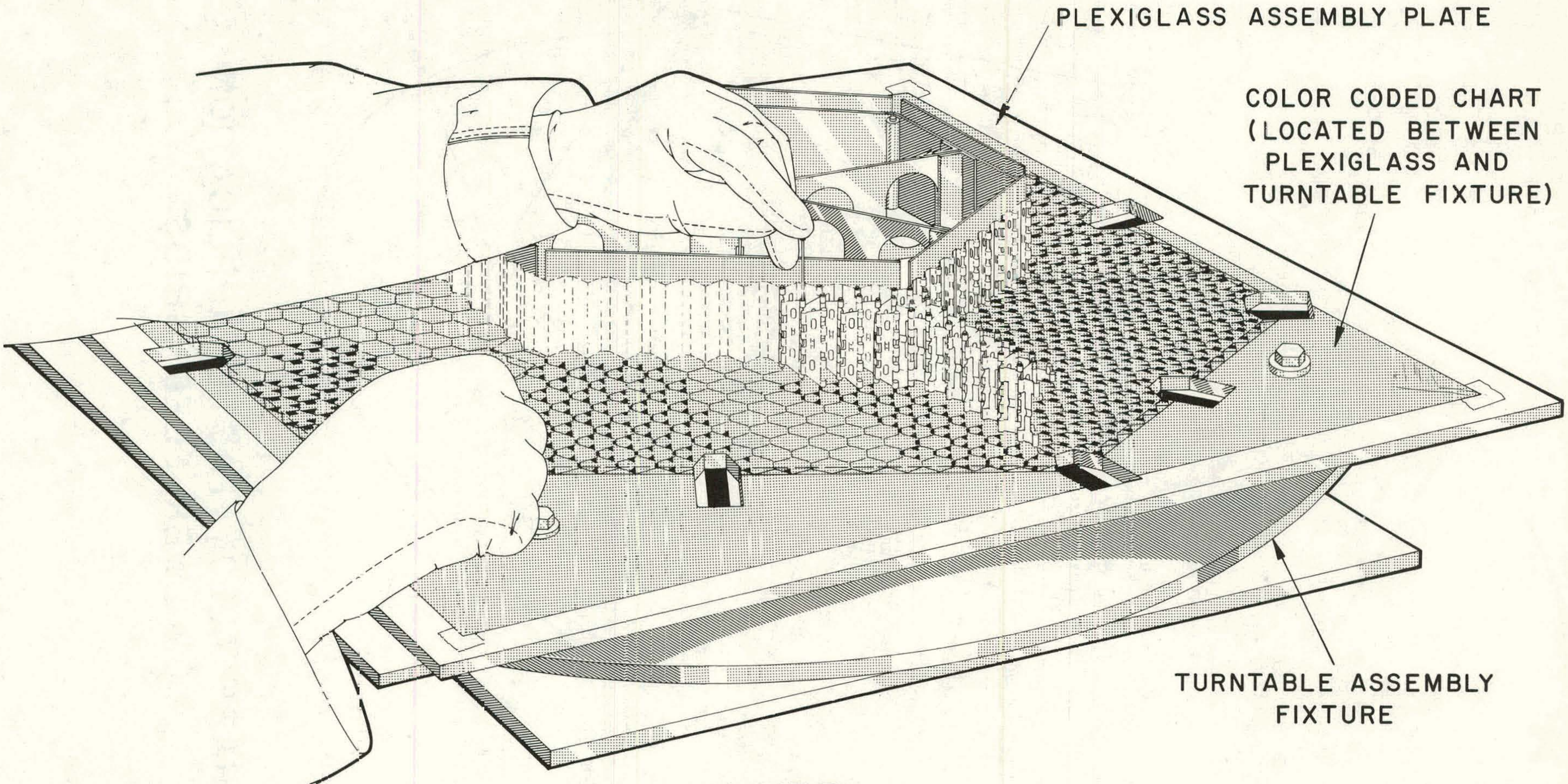
LWBR
SEED GRID
ASSEMBLY FIXTURING
(EXPLODED VIEW)

Figure 18



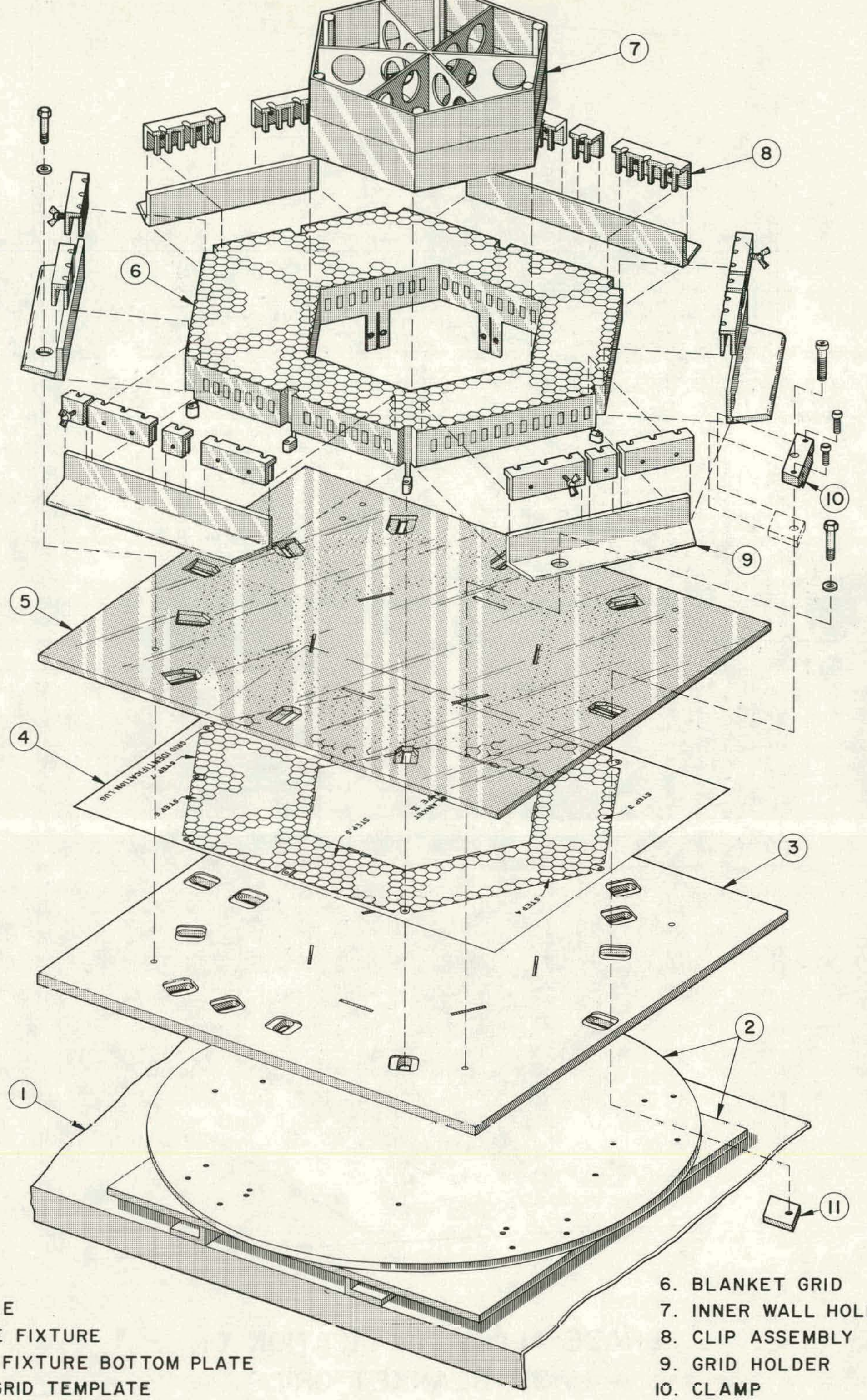
BRAZE ALLOY PASTE APPLICATION ON LWBR SEED GRIDS

Figure 19



LWBR
BLANKET GRID ASSEMBLY

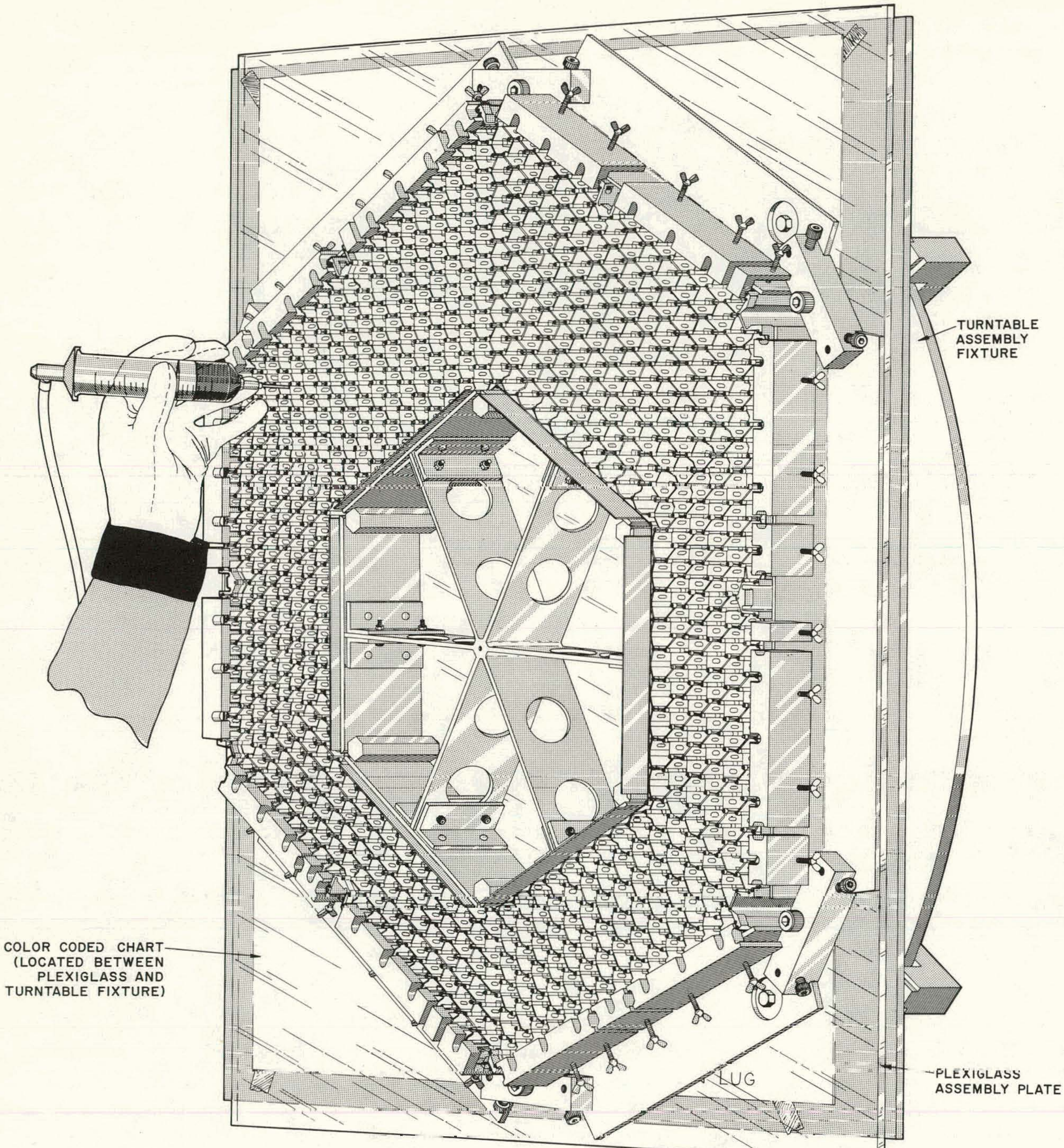
Figure 20



1. WORK TABLE
2. TURNTABLE FIXTURE
3. ASSEMBLY FIXTURE BOTTOM PLATE
4. BLANKET GRID TEMPLATE
5. PLEXIGLASS ASSEMBLY PLATE
6. BLANKET GRID
7. INNER WALL HOLDING FIXTURE
8. CLIP ASSEMBLY
9. GRID HOLDER
10. CLAMP
11. NUT

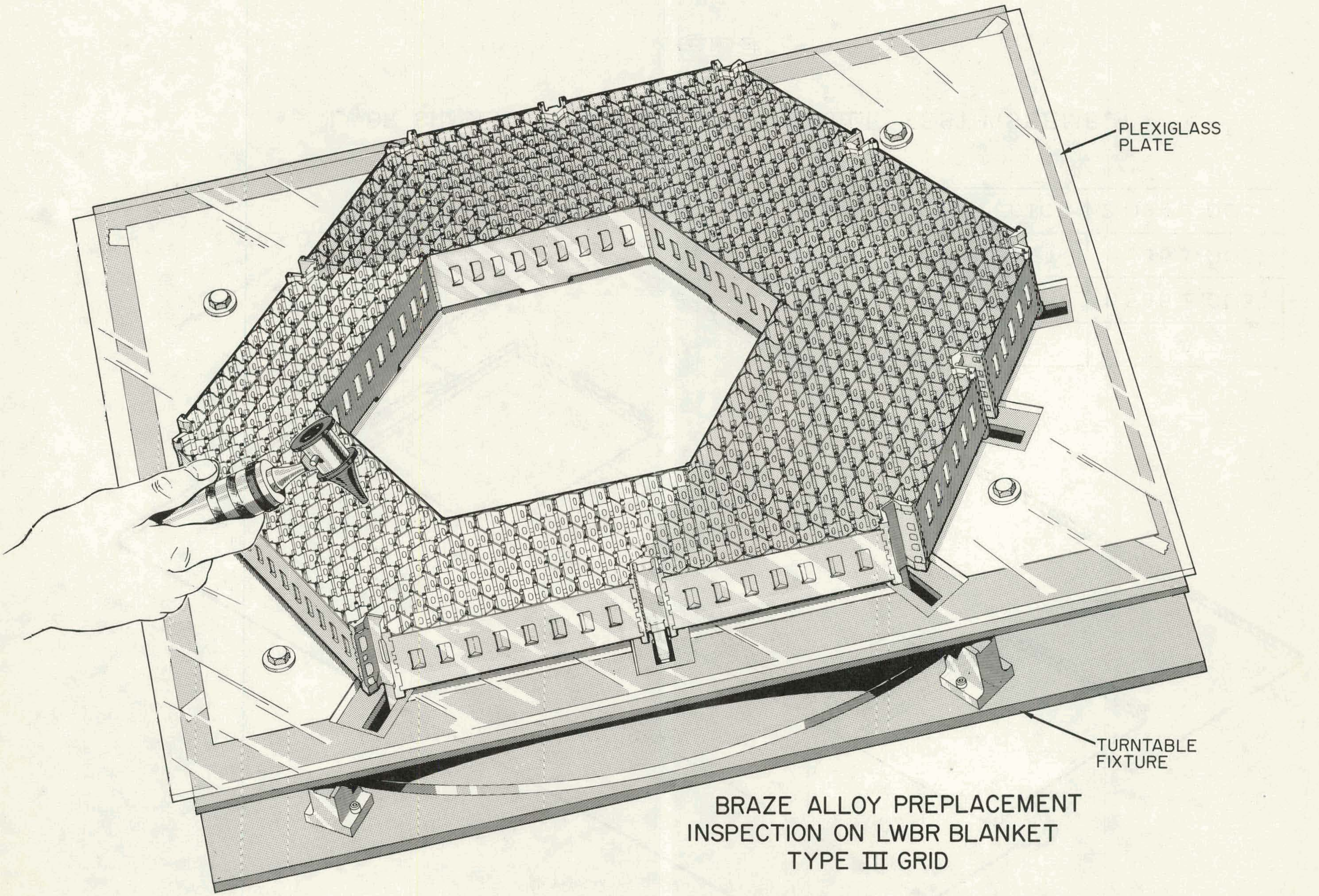
LWBR
BLANKET TYPE II ASSEMBLY FIXTURING
(EXPLODED VIEW)

Figure 21



BRAZE ALLOY APPLICATION ON
LWBR BLANKET GRIDS

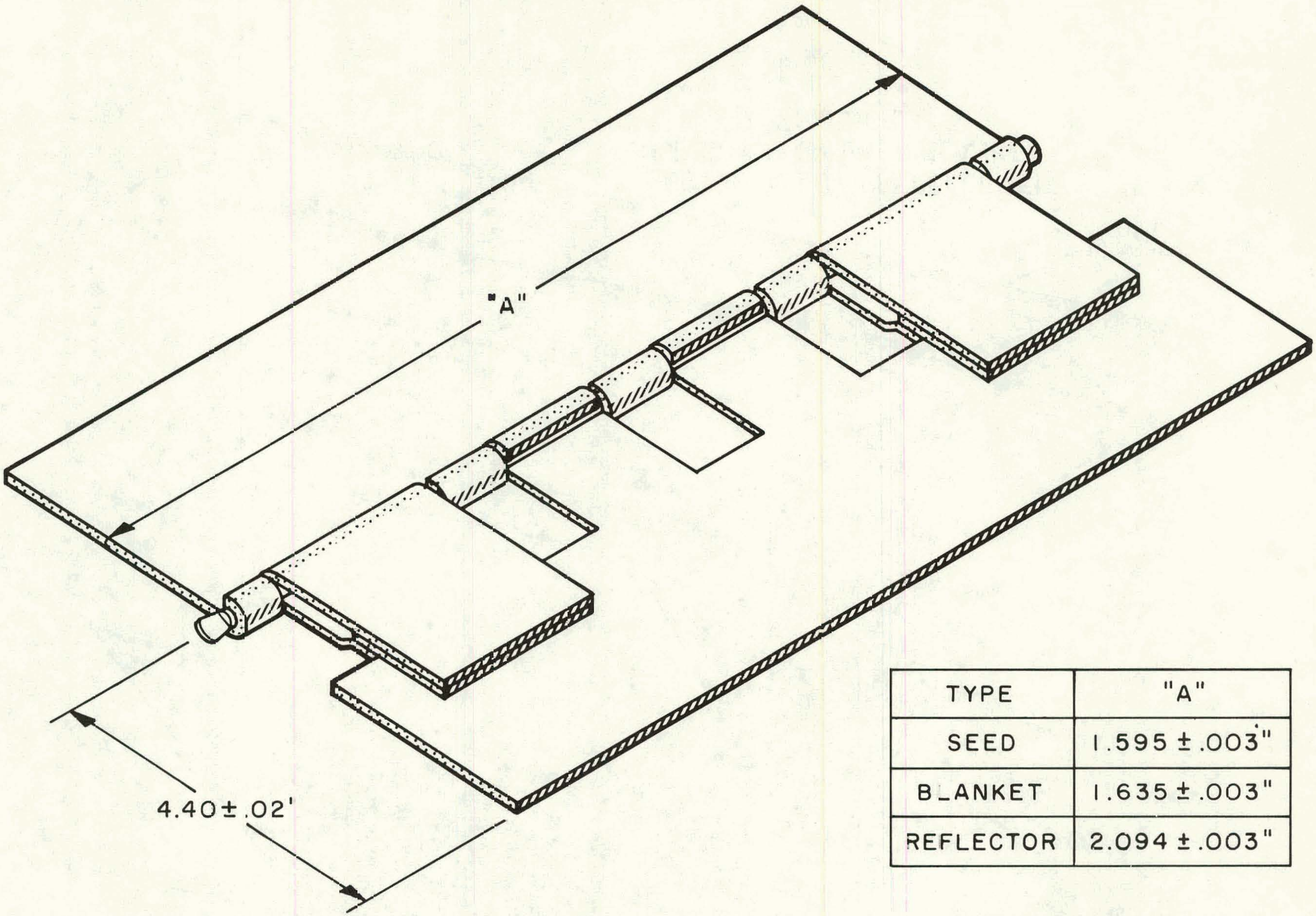
Figure 22



BRAZE ALLOY PREPLACEMENT
INSPECTION ON LWBR BLANKET
TYPE III GRID

FIGURE

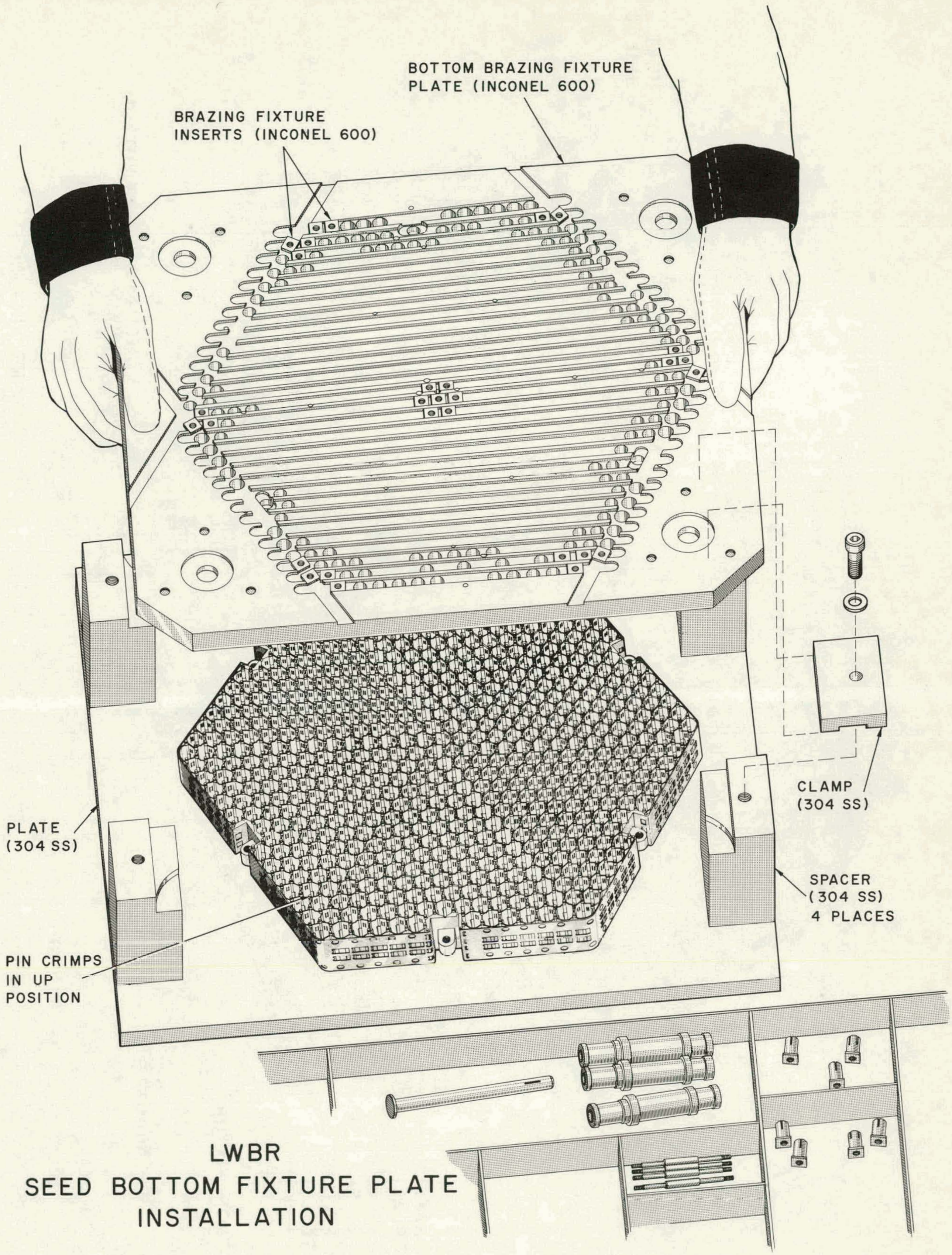
Figure 23



TYPE	"A"
SEED	1.595 ± .003"
BLANKET	1.635 ± .003"
REFLECTOR	2.094 ± .003"

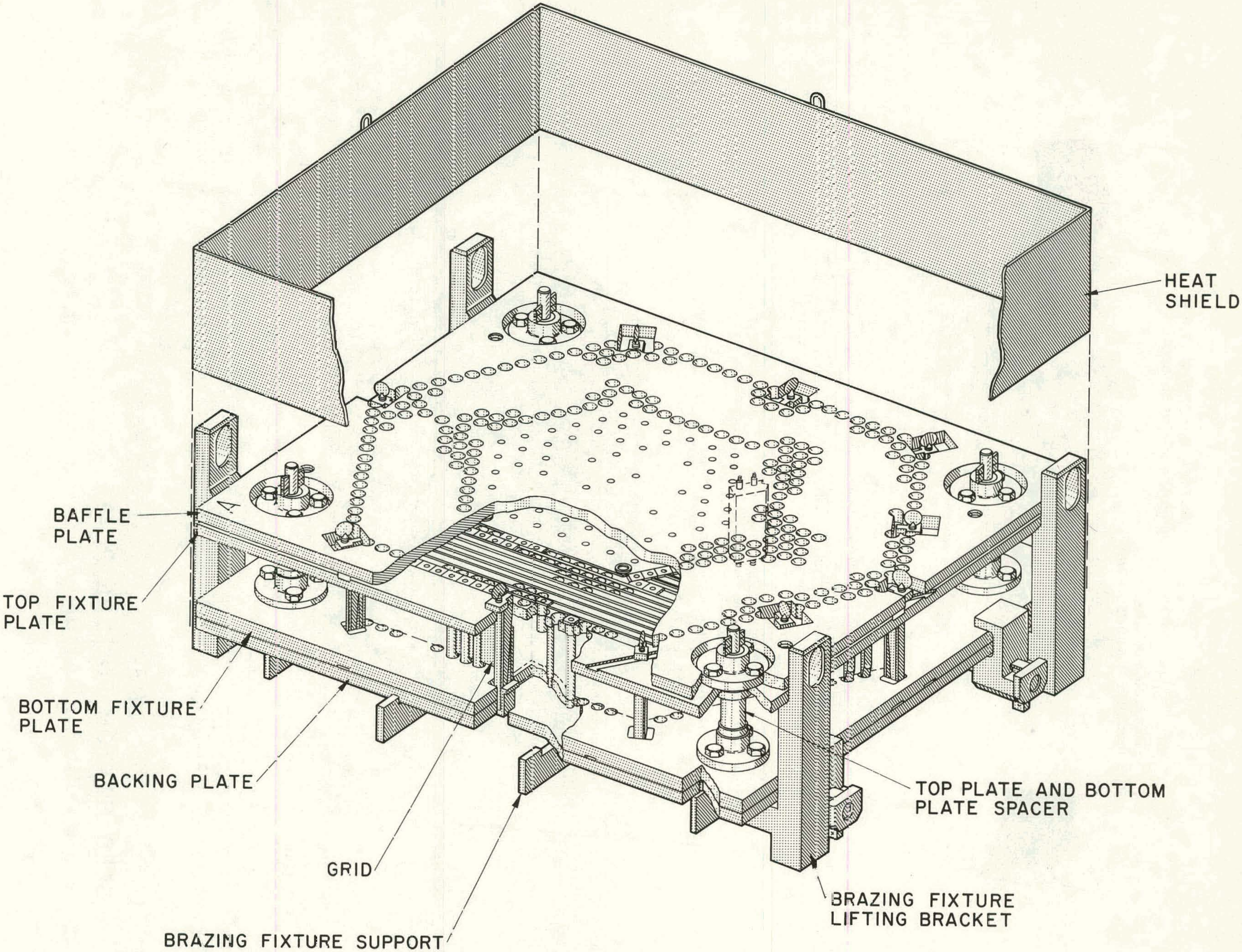
LWBR SIMULATED HINGE JOINT TENSILE TEST ASSEMBLY

Figure 24



LWBR
SEED BOTTOM FIXTURE PLATE
INSTALLATION

Figure 25



LWBR TYPE II BLANKET GRID
BRAZING FIXTURE ASSEMBLY

Figure 26

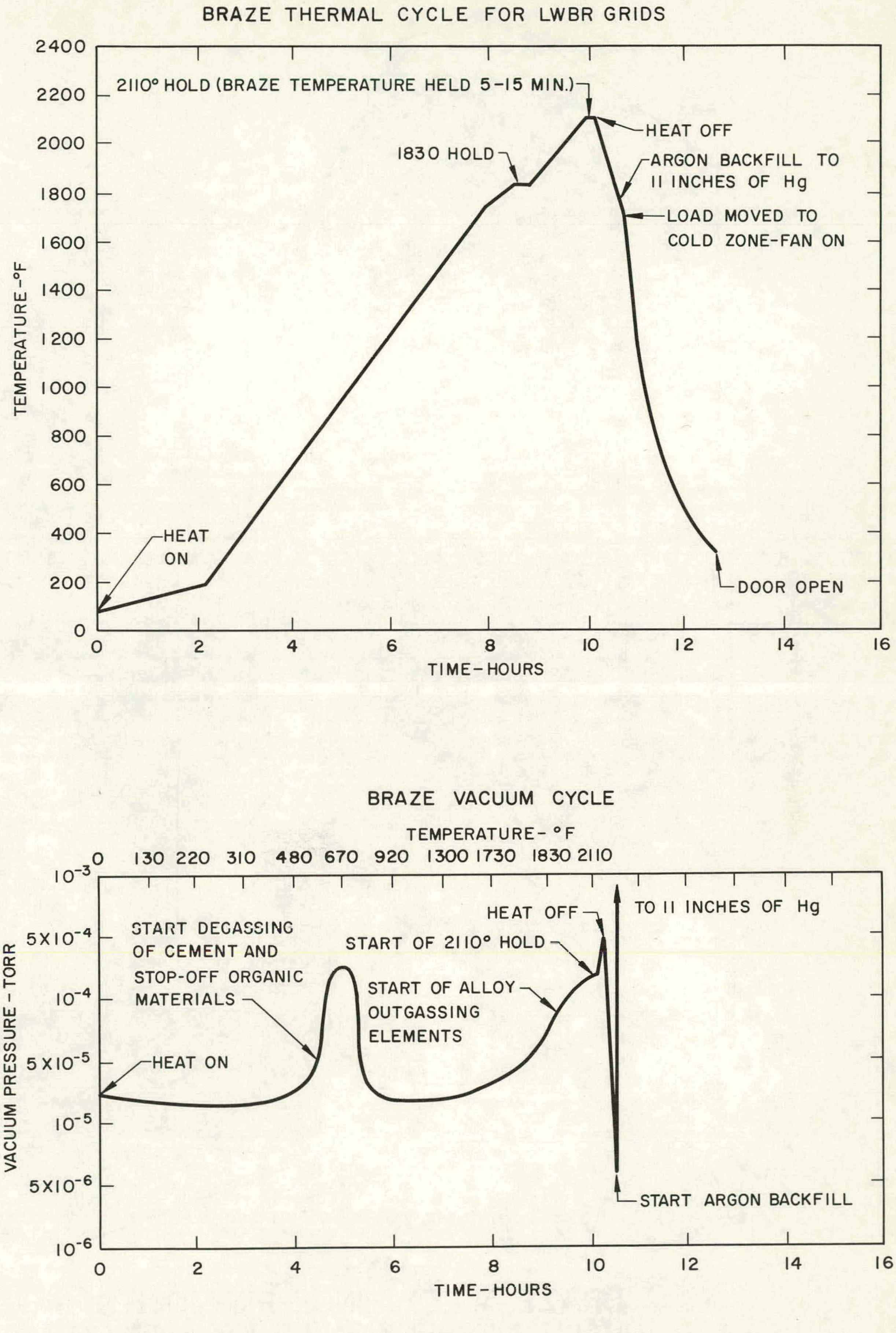
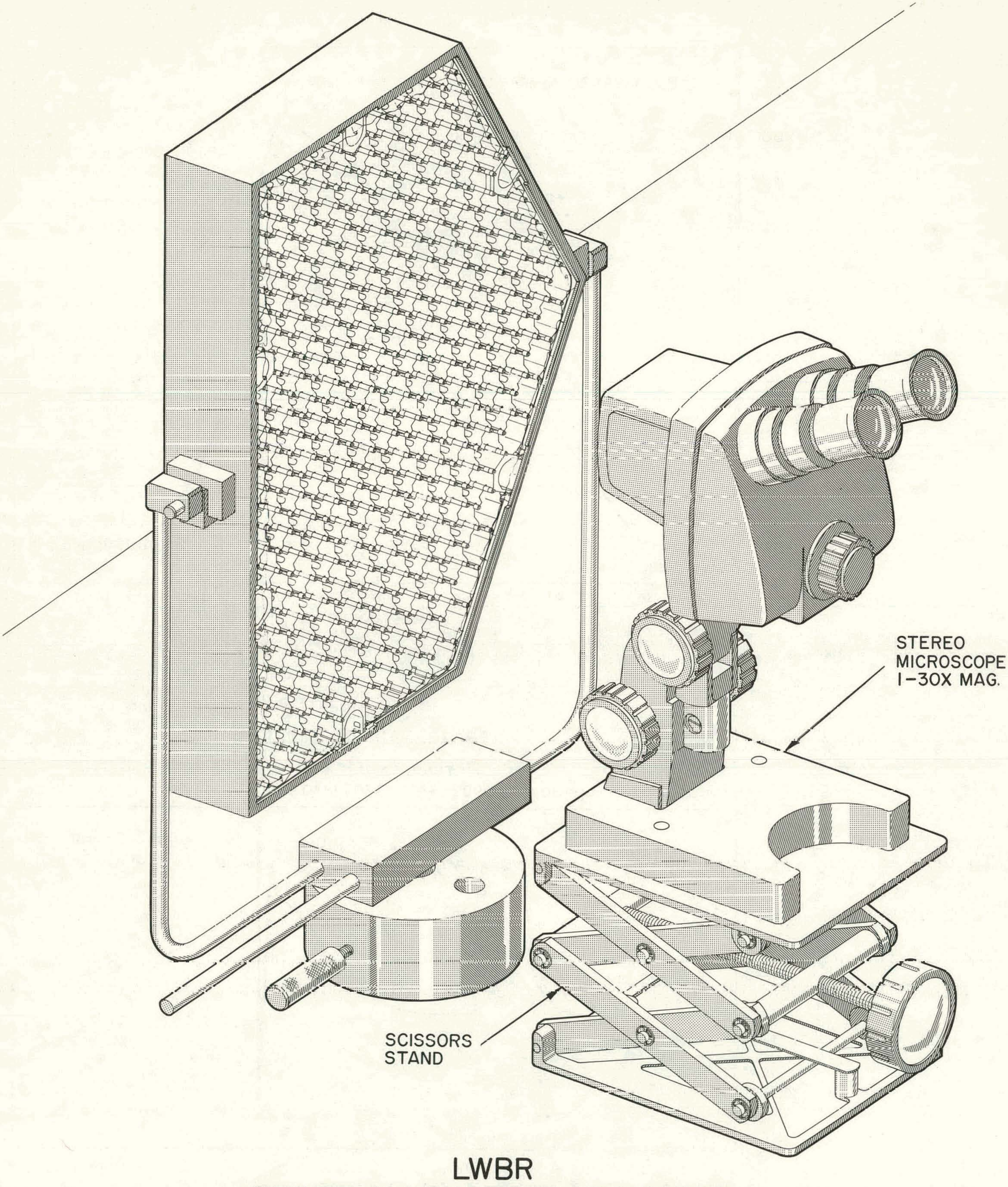
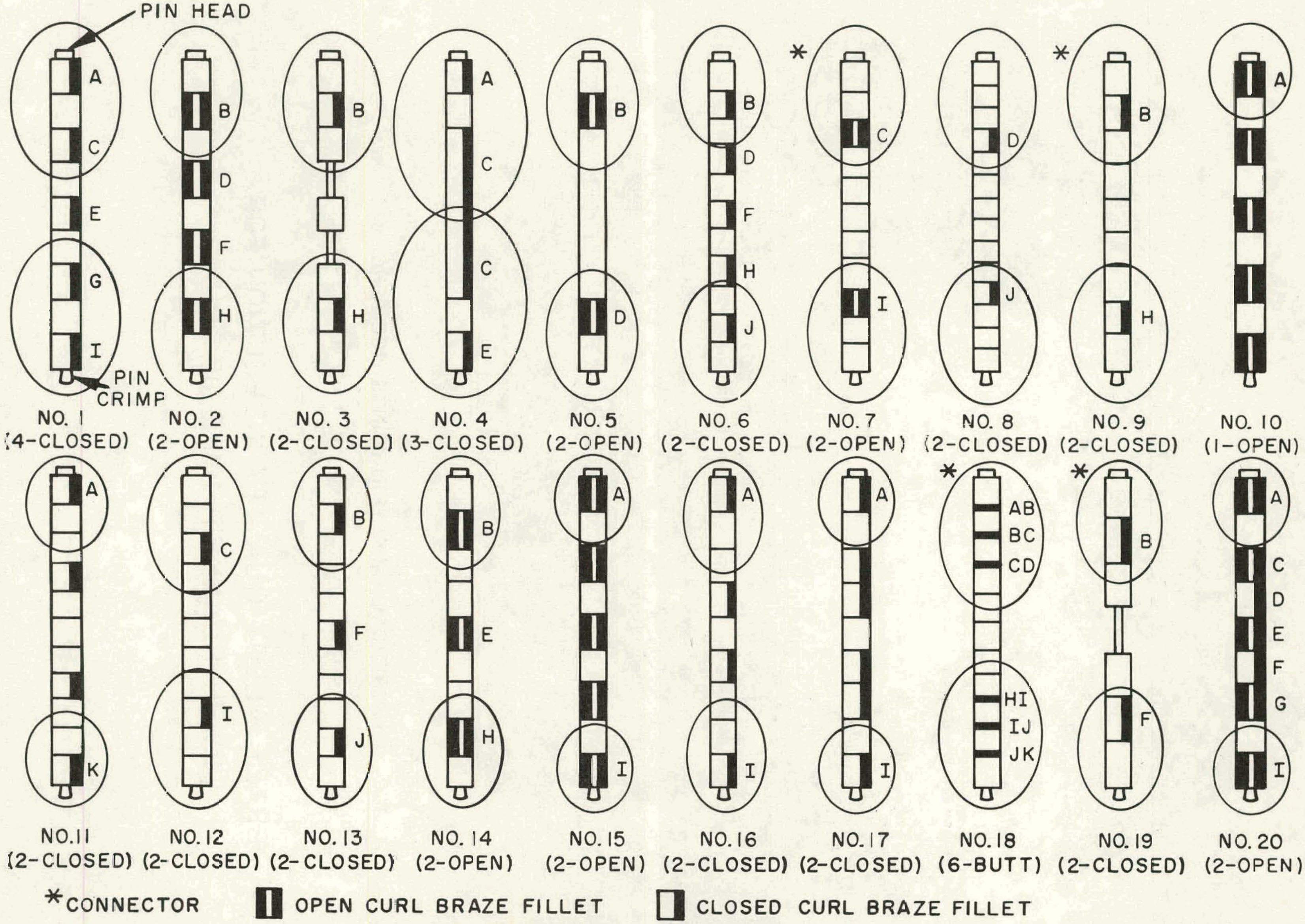

BRAZE THERMAL CYCLE FOR LWBR GRIDS
2110° HOLD (BRAZE TEMPERATURE HELD 5-15 MIN.)
HEAT OFF
1830 HOLD
ARGON BACKFILL TO 11 INCHES OF Hg
LOAD MOVED TO COLD ZONE-FAN ON
HEAT ON
DOOR OPEN
TEMPERATURE-°F
TIME-HOURS
BRAZE VACUUM CYCLE
TEMPERATURE-°F
0 130 220 310 480 670 920 1300 1730 1830 2110
TO 11 INCHES OF Hg
HEAT OFF
START OF 2110° HOLD
START DEGASSING OF CEMENT AND STOP-OFF ORGANIC MATERIALS
START OF ALLOY OUTGASSING ELEMENTS
HEAT ON
START ARGON BACKFILL
VACUUM PRESSURE - TORR
TIME-HOURS

Figure 27



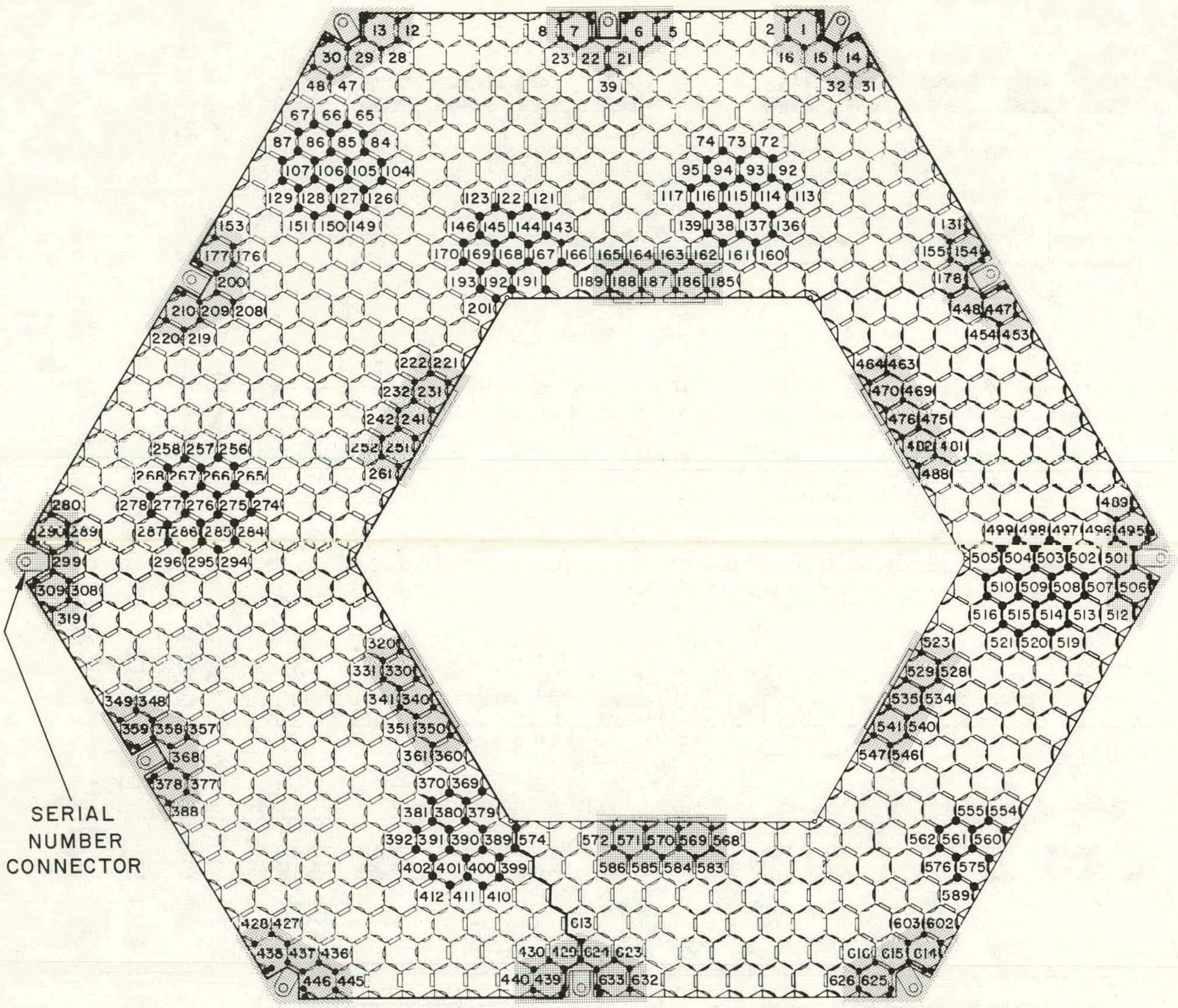
LWBR
BRAZE ALLOY HINGE-PIN-JOINTS
QUALITY INSPECTION AT 10X MAG. ON
TYPE IV RELECTOR GRIDS

Figure 28



HINGE-PIN BRAZE JOINT CURL DESIGNS FOR LWBR GRIDS

Figure 29



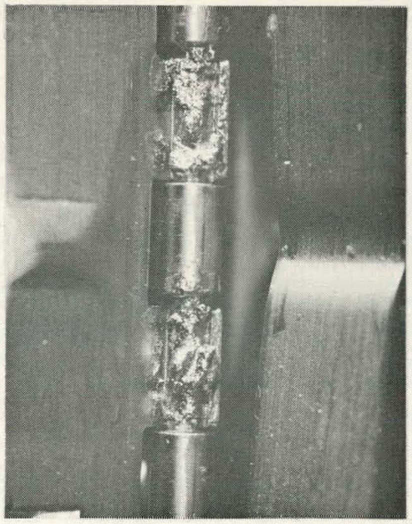
NUMBER

208 • CRITICAL HINGE-PIN JOINTS (100 PERCENT)

152 • NON-CRITICAL HINGE-PIN JOINTS (SAMPLE)

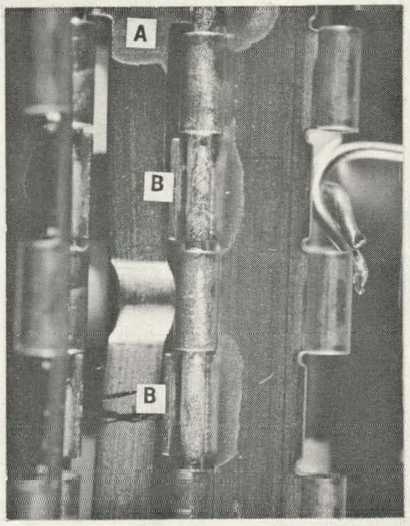
BRAZE ALLOY QUALITY INSPECTION FOR LWBR BLANKET TYPE III GRID

Figure 30



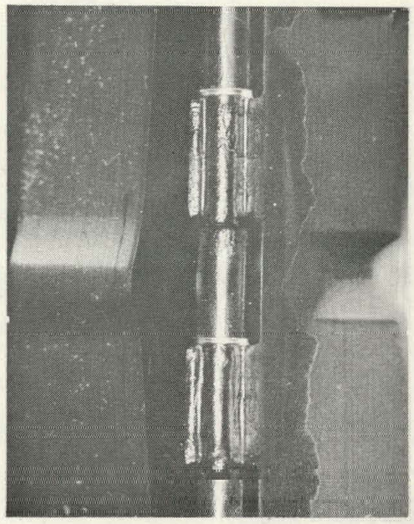
MAG. 10X

A



MAG. 10X

B



MAG. 10X

C

A. UNACCEPTABLE BRAZE JOINT. INCOMPLETE MELTING

B. UNACCEPTABLE BRAZE JOINTS.
EXCESSIVE BRAZE ALLOY ON SPRING WORKING SURFACE (A)
LACK OF BRAZE ALLOY FLOW AND BONDING IN THE OPEN CURLS (B)

C. ACCEPTABLE BRAZE ALLOY FLOW AND BONDING

BRAZE ALLOY FILLETS VISUAL STANDARDS FOR LWBR GRIDS

Figure 31

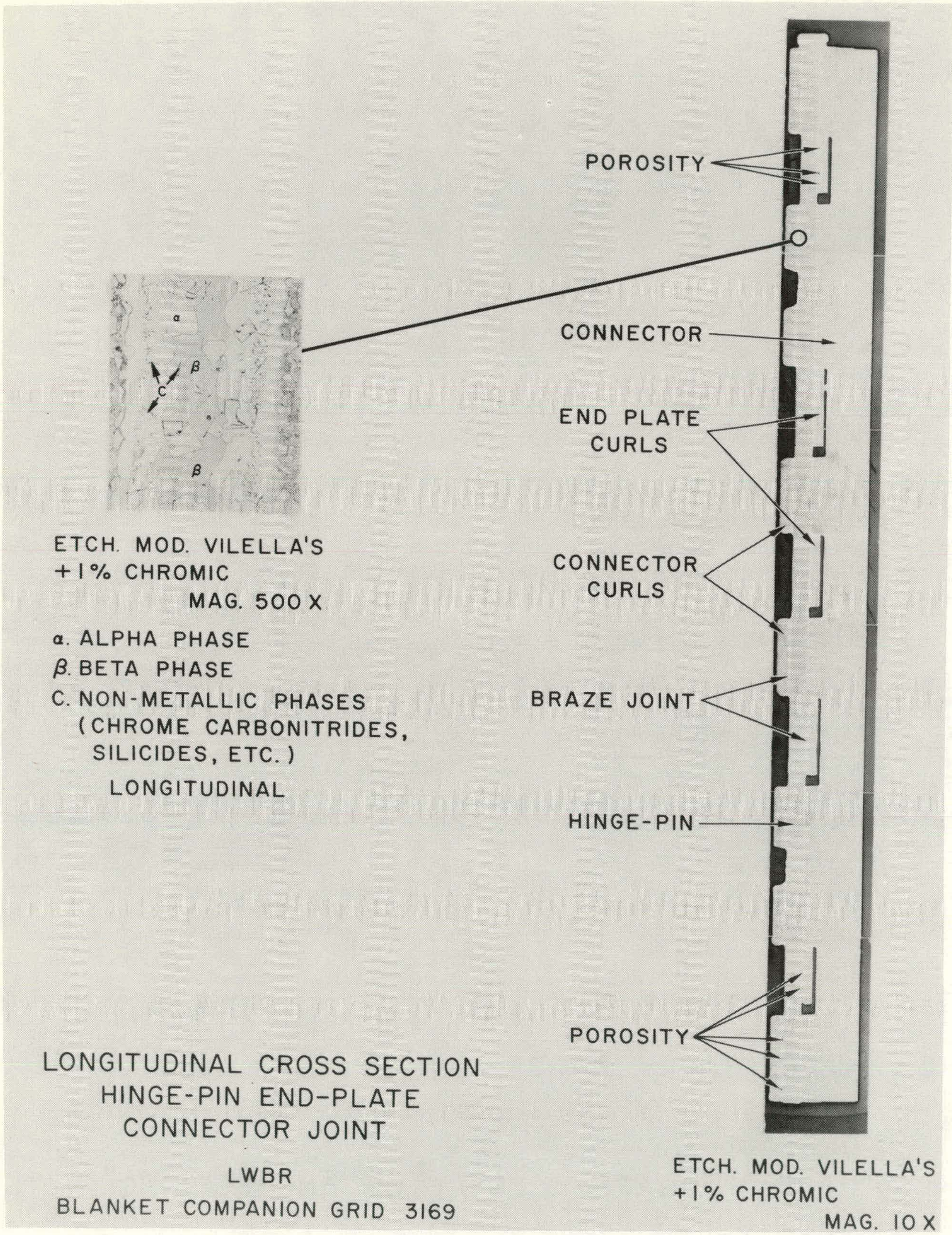
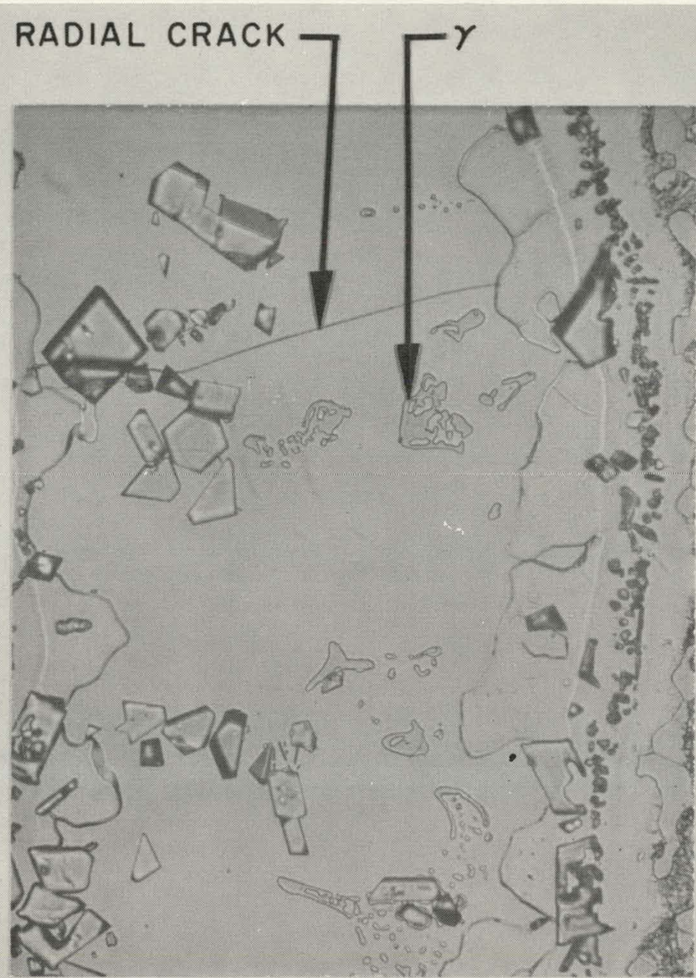

α
β
C
β
ETCH. MOD. VILELLA'S
+1% CHROMIC
MAG. 500 X
α. ALPHA PHASE
β. BETA PHASE
C. NON-METALLIC PHASES
(CHROME CARBONITRIDES,
SILICIDES, ETC.)
LONGITUDINAL
POROSITY
CONNECTOR
END PLATE
CURLS
CONNECTOR
CURLS
BRAZE JOINT
HINGE-PIN
POROSITY
LONGITUDINAL CROSS SECTION
HINGE-PIN END-PLATE
CONNECTOR JOINT
LWBR
BLANKET COMPANION GRID 3169
ETCH. MOD. VILELLA'S
+1% CHROMIC
MAG. 10 X

Figure 32

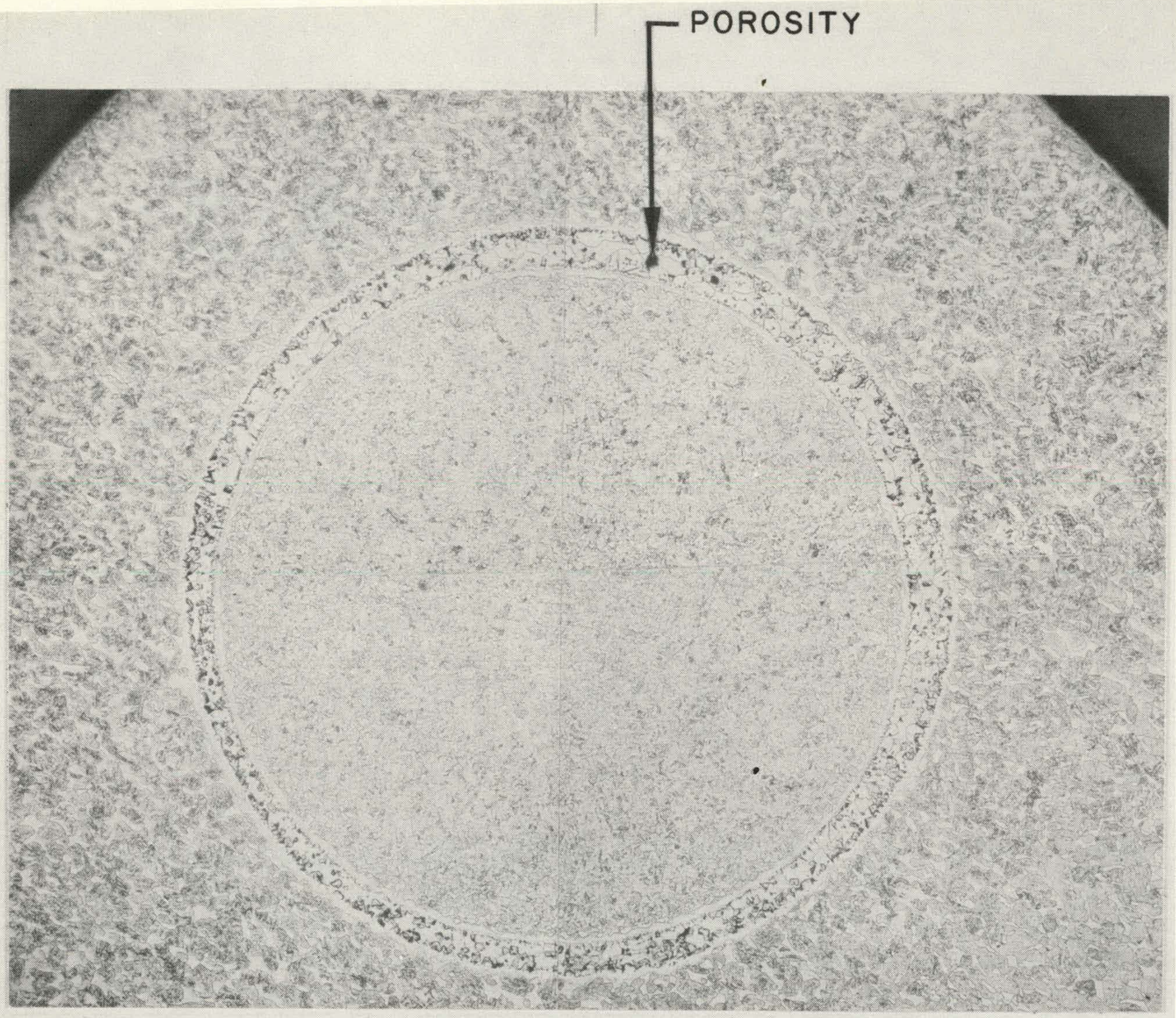


ETCH: MOD. VILELLA'S +1% CHROMIC MAG. 500X

GAMMA PHASE AND RADIAL CRACK IN BETA PHASE

LWBR SEED COMPANION GRID 0160

Figure 33

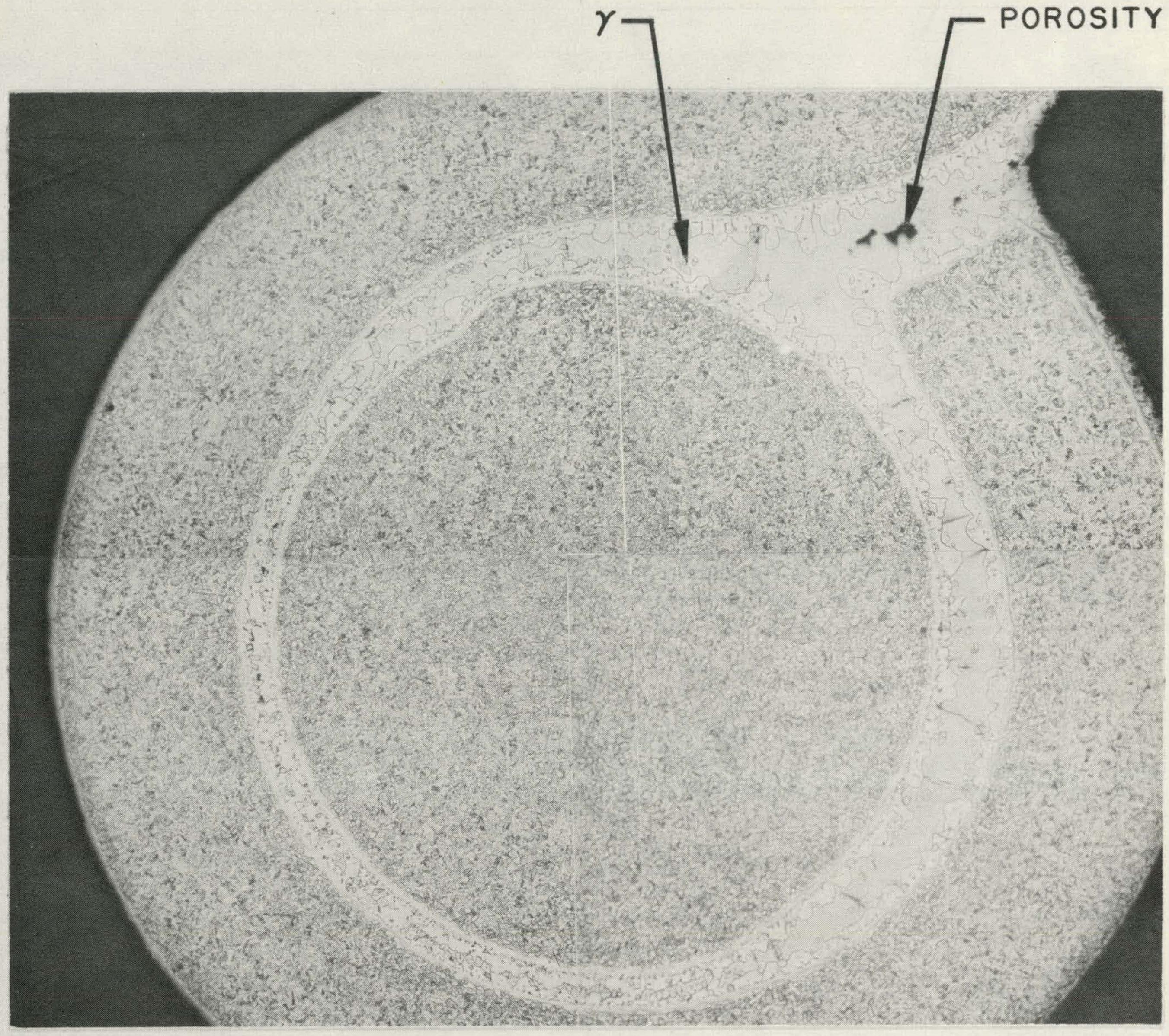


ETCH: MOD. VILELLA'S + 1% CHROMIC MAG. 100 X

TRANSVERSE CROSS-SECTION HINGE-PIN CONNECTOR JOINT

LWBR BLANKET COMPANION GRID 3169

Figure 34

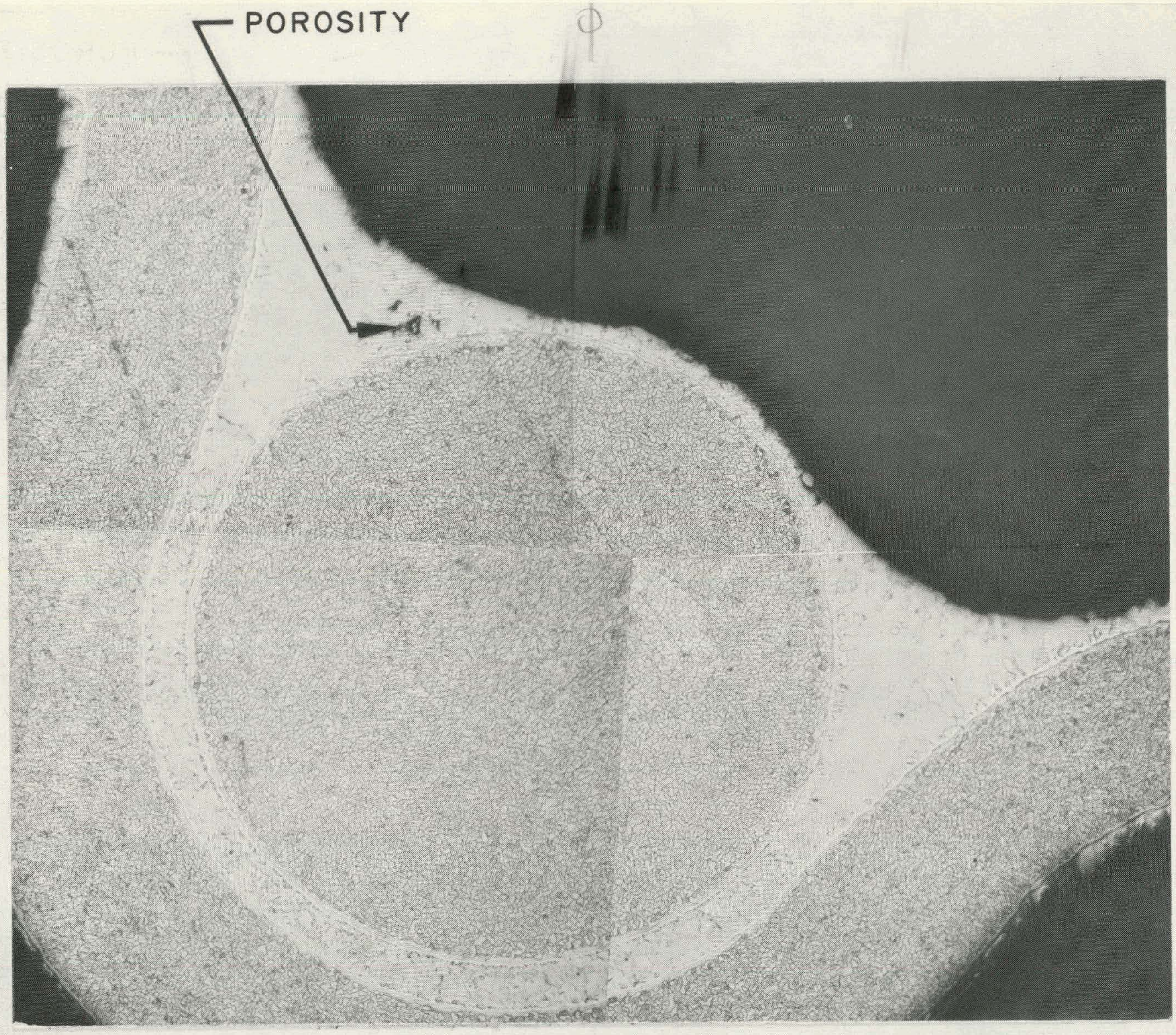


ETCH: MOD. VILELLA'S + 1% CHROMIC MAG. 100 X

TRANSVERSE CROSS-SECTION HINGE-PIN
SHEET METAL CLOSED CURL JOINT

LWBR BLANKET COMPANION GRID 3169

Figure 35



ETCH: MOD. VILELLA'S + 1% CHROMIC MAG. 100 X

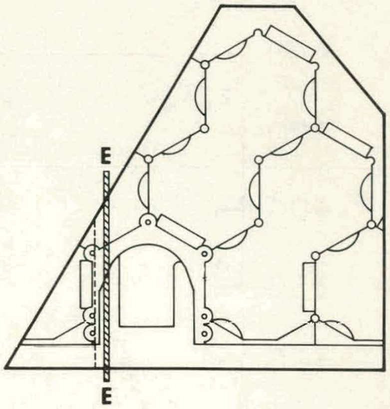
TRANSVERSE CROSS-SECTION HINGE-PIN
SHEET METAL OPEN CURL JOINT

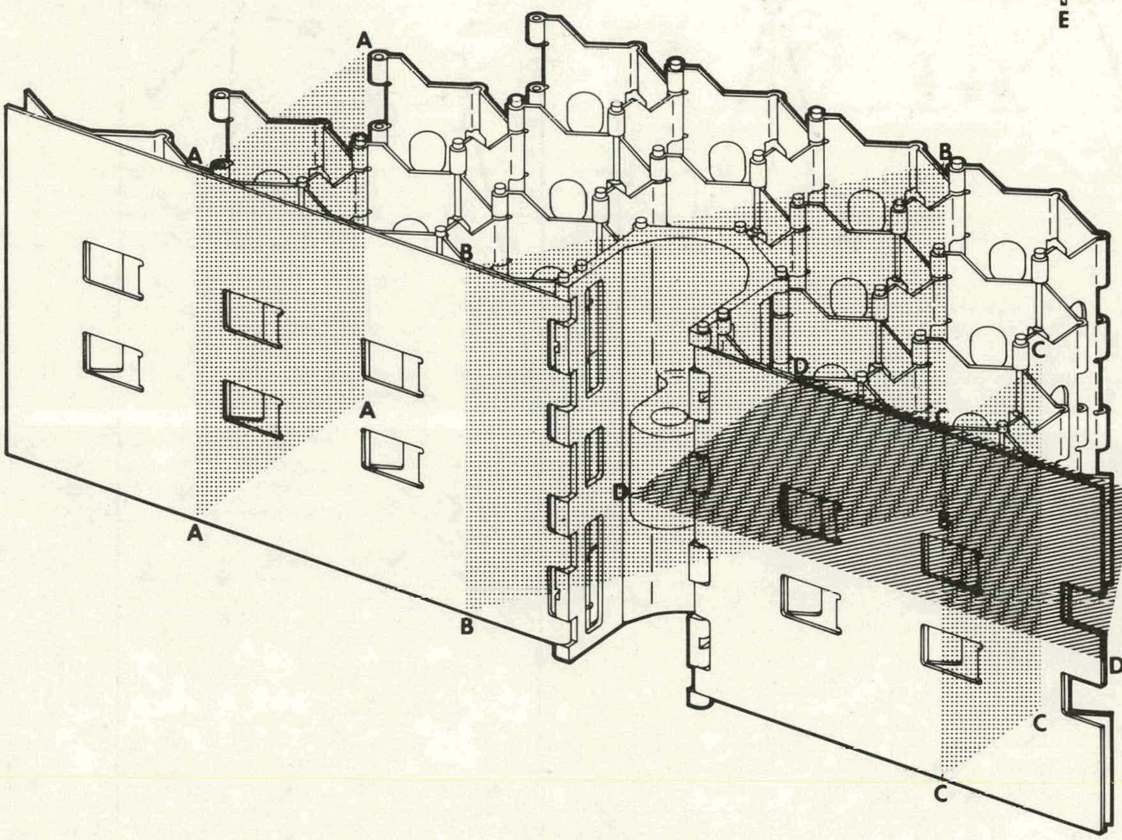
LWBR REFLECTOR COMPANION GRID 4116

Figure 36

METALLOGRAPHIC EXAMINATION CROSS-SECTIONS

A-A LONGITUDINAL CROSS-SECTION
END-PLATE SHEET METAL HINGE-PIN JOINTS
B-B INITIAL CUT FOR CONNECTOR LONGITUDINAL
CROSS-SECTION
C-C LONGITUDINAL HINGE-PIN SHEET METAL JOINTS
D-D TRANSVERSE CROSS-SECTION HINGE-PIN
SHEET METAL AND HINGE-PIN END-PLATE CONNECTOR
JOINTS
E-E LONGITUDINAL HINGE-PIN END-PLATE CONNECTOR
JOINTS





LWBR
REFLECTOR COMPANION GRID

Figure 37

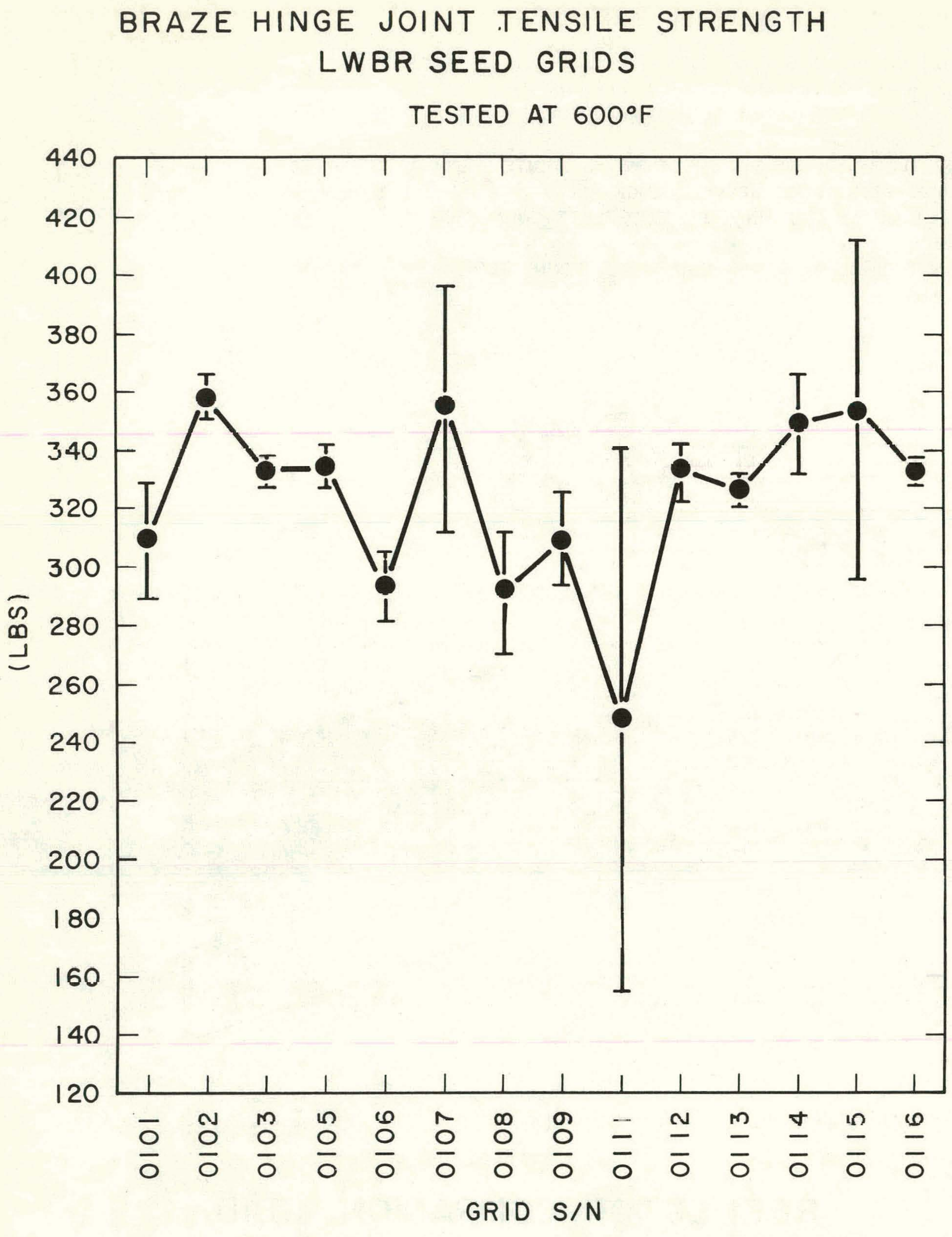

BRAZE HINGE JOINT TENSILE STRENGTH
LWBR SEED GRIDS
TESTED AT 600°F
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
(LBS)
0101
0102
0103
0105
0106
0107
0108
0109
0111
0112
0113
0114
0115
0116
GRID S/N

Figure 38

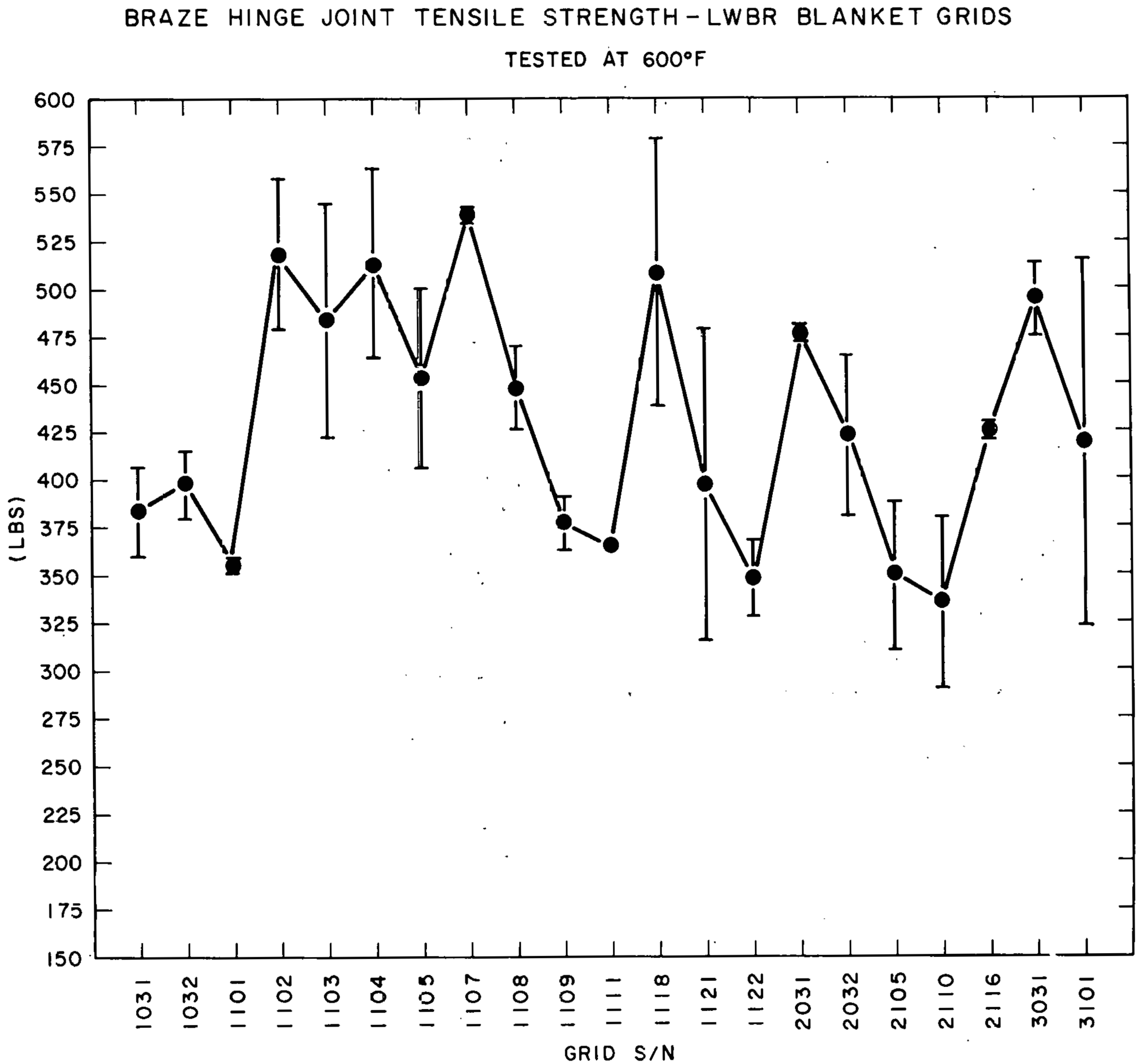

BRAZE HINGE JOINT TENSILE STRENGTH - LWBR BLANKET GRIDS
TESTED AT 600°F
600
575
550
525
500
475
450
425
400
375
350
325
300
275
250
225
200
175
150
(LBS)
1031
1032
1101
1102
1103
1104
1105
1107
1108
1109
1111
1118
1121
1122
2031
2032
2105
2110
2116
3031
3101
GRID S/N

Figure 39

BRAZE HINGE JOINT TENSILE STRENGTH
LWBR REFLECTOR TYPE V GRIDS

TESTED AT 600°F

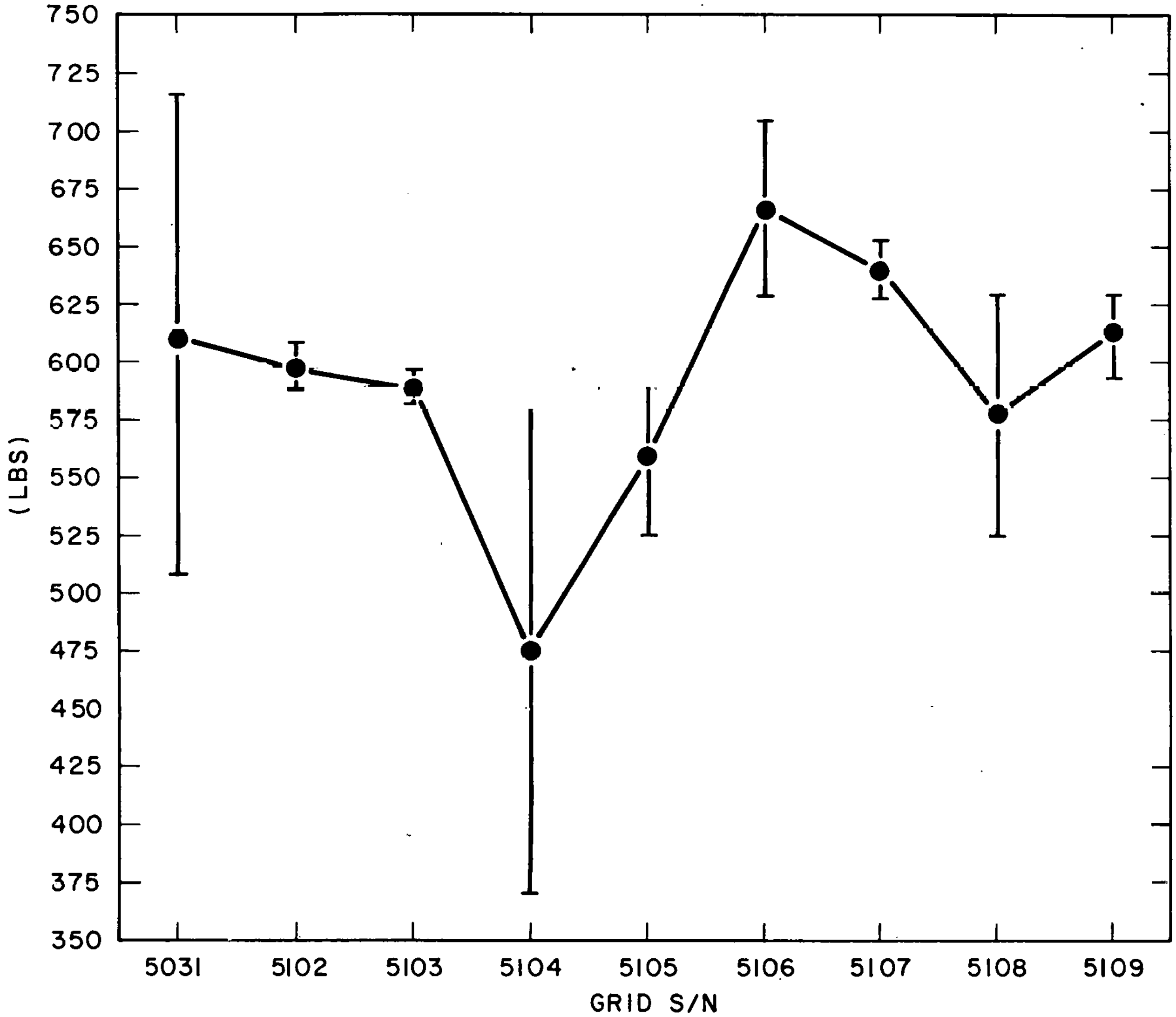


Figure 40