MASTER

NEUTRAL BEAM SOURCE COMMERCIALIZATION STUDY

Hughes Research Laboratories, 3011 Malibu Canyon Road, Malibu, CA 90265

June 1980

Order No. 315002
Final Report

Prepared for

LAWRENCE BERKELEY LABORATORY
One Cyclotron Road
Berkeley, California 94720

Prepared for the U. S. Department of Energy
under Contract No. W-7405-ENG-48

NEUTRAL BEAM SOURCE COMMERCIALIZATION STUDY

Order No. 315002

FINAL REPORT

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High Voltage Technology Department

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ACKNOWLEDGMENTS

This report was prepared by Dr. H.J. King, Manager of the High Voltage Technology Department, who served as Program Manager during the final several months of source fabrication and assembly. Mr. D. Schnelker managed the program through the initial phases of design and parts procurement. Major contributions to the successful completion of the project were made by Mr. Paul Sumner and Mr. R. Pruss, who assembled the compounds and by Mr. C. Comstock, who was responsible for the drawing package.

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SECTION 1

INTRODUCTION

High-current, high-voltage ion beams that can subsequently be neutralized by charge exchange are acknowledged as a key element in the recent successful heating experiments with magnetically confined plasmas. As these experiments progressed, it was recognized by those planning future large fusion energy installations that large numbers of such neutral beam sources would be required. It seemed likely that an industrial supplier could be developed for the production phase of these projects so as to remove the burden of source manufacture from the National Laboratories and permit them to continue the advanced development process to meet the needs of next-generation machines.

A preliminary phase of the contract reported here was used to familiarize the HRL source manufacturing group with the neutral beam source developed at Lawrence Berkeley Laboratories (LBL) under the group headed by Dr. Robert Pyle. During this preliminary phase, the feasibility of several potentially useful design improvements was evaluated both analytically and experimentally. Following a review by LBL designers, these changes were incorporated into the Phase II program reported here.

The basic tasks of this Phase II project were to

- Generate a set of design drawings suitable for quantity production of sources of this design
- Fabricate a functional neutral beam source incorporating as many of the proposed design changes as proved feasible
- Document the procedures and findings developed during the contract.

As described below, these tasks have been accomplished and represent a demonstrated milestone in the industrialization of this complete device.

SECTION 2

SUMMARY

The quantitative accomplishments and observations are described in the narrative and appendices which follow. This section gives a more general overview of the program.

A. DRAWINGS AND PROCEDURES

There is a much greater disparity between the drawing formats and procedures used at the National Laboratories and an industrial firm such as Hughes Aircraft Company than was originally realized. Although each system is quite functional in its own environment, we found it necessary to create a totally new set of drawings to satisfy our procurement, manufacturing, and quality-assurance procedures. Basically, our manufacturing procedures require a sequence of drawings, each one of which represents a single step or procedure. This set of drawings replaces the single, more comprehensive LBL drawing that would typically be used by a machinist or technician who is very familiar with the end product on which he is working and who might logically follow a single part through several stages of assembly as he fabricates a single prototype source.

B. DESIGN MODIFICATIONS

Several modifications were suggested as part of the Phase I Design Study. All of these were evaluated; however, not all were incorporated into the final delivered hardware. Those incorporated were:

- Active metal brazed ceramic assembly
- Gun-drilled coolant lines in the plasma source flanges
- Rails electron-beam welded into their holders
- Metallic "C" seals used for water line connections

Those changes tried but abandoned were:

- Hat structures made from molybdenum (delivered hats are 304 stainless steel)
- "C" seals in plasma chamber (delivered chamber has "O" ring seals)

REFERENCE PRINT
 Reproduction of original drawing of parts
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 UNLESS OTHERWISE SPECIFIED
 TOLERANCES ARE IN INCHES
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1	J1096127	ACCELERATOR ASSEMBLY		9
1	J1096009	PROBE PLATE		2
1	D1029832	NEUTRAL BEAM SOURCE		1
1	CODE IDENT	PART NO OR IDENTIFYING NO		1
1	CODE IDENT	IDENTIFYING NO		1
PARTS LIST				
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1096000				
SCALE 2:1				
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REVISION SPECIFIED

Figure 1. Neutral beam injector.

SECTION 3

NEUTRAL BEAM SOURCE CONSTRUCTION

A. DESIGN

The design goals for this program are enumerated in the final report for Phase I and need not be discussed in detail here. In brief, however, the goals were to

- Have an industrial supplier produce a functional neutral beam source of the LBL design (as of March 1978).
- Define design modifications that would make the source more "manufacturable" (Phase I) and then implement these modifications during source construction (Phase II).
- Not jeopardize source performance since the end product is to assume a functional role in Tokamak Fusion Test Reactor (TFTR) tests.

The resultant program has succeeded in achieving all three of these goals. As often occurs in a development program of this complexity, several modifications to the original Phase I plan were necessary to complete source construction successfully. The several aspects of the program are discussed in the following sections, along with comments and recommendations which may pertain to future designs.

1. Plasma Source

The plasma source is a brazed OFHC copper assembly with one stainless-steel flange as shown in drawing (Figure 2). The stress analysis presented in Appendix A indicates that there is a structural factor of safety of four or greater for all components when the chamber is subjected to its nominal loading of 2 atm due to an external pressure of SF_6 and an internal vacuum.

In contrast to the coolant tubes brazed to the external surfaces of the chamber, our design incorporates internal water channels in the flanges. These were "gun drilled" prior to assembly. A copper coolant channel with a square cross section was formed to cool the chamber wall, which was too thin for internal cooling lines.

For future chambers, we would seriously consider machining the entire chamber (including flanges) from a solid copper billet and making all coolant lines internal to the walls and flanges. This would permit excellent control over finished dimensions and would eliminate a complicated brazing operation. It would, however, add significantly to the overall weight and would eliminate the ability to make one flange stainless steel.

The insulating gaskets between the several copper plates and sub-assemblies were made from polished aluminum sheet which was subsequently hard anodized by the Sanford Hard Anodizing process to a depth of 0.004 in. These gaskets performed well once proper dimensional clearances were defined and careful handling procedures had been established in the assembly area.

The assembly was originally designed to be sealed with "C" seals manufactured by Pressure Sciences Incorporated. However, these seals were not used (see Section 3.B.1), and Buna N "O" rings were substituted for them. If O rings are to be used in the future, the grooves should be designed to capture the O rings to ease assembly.

The filament chucks are threaded molybdenum rods screwed into the copper mounting plates at one end and split to receive the tungsten wire hairpin filaments at the other. This is the standard LBL design which was tested at HRL during Phase I.

Captured screws are used to attach the arc chamber to the probe plate to prevent the mounting hardware from being lost if remote handling equipment is used to disassemble the source.

2. Probe Plate

The probe plate is shown in Figure 3. As with the arc chamber, it incorporates gun-drilled internal cooling channels.

3. Insulator Column

a. Ceramic Assembly

The series of tests leading to the design of the brazed Al_2O_3 /titanium joints are discussed in detail in the Phase I final report. The resulting design of both the brazed ceramic/metal joint and the

1. TURNING MATERIAL TO PE OF MC COPPER OR REPAIR/REWORK TUBING
2. C-SEAL RING NUT FROM PRESSURE SCIENCE INCORPORATED HAVE OLD BATHING PEEK, BELTSVILLE, MARYLAND 20705
3. CHAMFER ALL TAPPED HOLES
4. ASSEMBLE PER HVT-MP-005
5. MAKE PER NO. 1006000 PER MPB-3, TYPE 1, CLASS 2, JIS HIGH CHARACTERISTICS. LOCATE AS SHOWN
6. DIMENSIONS ARE SYMMETRICAL ABOUT CENTER LINES (C) ESTABLISHED BY DATUMS. (C) & (C)
7. ALL SURFACES TO BE 1/16" OR BETTER
8. REMOVE ALL BURRS AND BREAK SHARP EDGES
- NOTES: UNLESS OTHERWISE SPECIFIED

4 PROBE PLATE ASSEMBLY

11

welded flange assembly are shown in Figure 4. The ceramic backup ring equalizes the stresses at the braze joint so as to permit strong, reliable assemblies.

The requirement to active metal braze this assembly dictates the use of high-quality, high-density (94%) aluminum oxide ceramics and titanium flanges. The similarities in thermal expansion coefficient and the relatively low temperature required for the braze are essential to the successful brazing of the large pieces required here.

The titanium flanges are designed to facilitate welding. Through holes are provided for water passages with the internal seals to the water lines leading to the rails being made with metal "C" seals. This is illustrated in Figure 4.

As shown in Figure 4, the corona rings are machined to conform to the desired cross section and to fit the ceramic/metal assembly. Although the design and function of these parts are straightforward, they are very expensive to fabricate in their present form. As future sources are designed, the various electrical/mechanical tradeoffs should be reviewed and these parts simplified mechanically if at all possible.

b. Grid Support Structure (Hat) Assemblies

Our Phase I report recommended that these hat assemblies be manufactured entirely from molybdenum rather than stainless steel as used by LBL in their prototype sources. A prototype was manufactured in Phase I, and, after great difficulties, the four necessary hats were manufactured during Phase II. Unfortunately, the resultant structures were very brittle, especially at the welds. Ultimately, the three hats used to mount the gradient, suppressor, and exit grids were replaced with stainless-steel units similar to the LBL design. The flat molybdenum source grid mount was retained.

Our parts were hand-formed and individually machined to save time once the decision to change materials was made. If these parts are to be made in quantity, various fabrication techniques that can be applied to stainless steel but not to molybdenum (such as deep-drawing) should be investigated before the design is frozen.

The hats are designed to mount into the ceramic column at one mounting point in each of the four corners. This permits simplicity in mounting and adjusting the various rail positions, but does not take advantage of the very rigid ceramic flanges which could be used to stiffen the "brim" of the hats if more attachment points had been used.

c. Rail/Rail Holders

The rails are straight sections of molybdenum rod purchased from a vendor in the shape dictated by the LBL computer analysis (see Figure 13, below).

There are 43 equally spaced rails in each of the source, gradient, suppressor, and exit rail assemblies. As shown in Figure 5, each set is held like rungs in a ladder by a pair of water-cooled rail holders, which are in turn screwed to their respective hats. As shown in Figure 6, the rail holders are slotted to accept the ends of the rails. One end of each rail is electron-beam welded to its respective rail holder. The other end of the rail is left free to slide in its mounting slot in the opposite rail holder as thermal transients cause expansion and contraction. The high precision required for both the rails and rail holders is readily attained with computer-controlled machines. We successfully used a vendor-owned wire cut electric discharge machine rather than a broach to produce the triangular slots required for the source rails. This versatile technique would be adaptable to bowed or curved electrode systems should they be required.

In keeping with the all-molybdenum structure described in our Phase I report, our original design for Phase II included all-molybdenum coolant water lines on the rail holders. With care, it was possible to bend the molybdenum tubing to the prescribed shapes and to electron-beam weld it to the rail holders. We found, however, that even during very careful handling the molybdenum tubing developed leaks at the bends due to the slight torquing action that inevitably occurs as a tube with right-angled or S-shaped bends is handled. Our design was subsequently modified to include molybdenum tubing only along the edges of the rail holders with stainless-steel extensions

SECTION B-B

ITEM NO.		DESCRIPTION	QTY	UNIT
1	1	ACCELERATOR ASSEMBLY	1	ASSEMBLY
2	1	ACCELERATOR ASSEMBLY	1	ASSEMBLY
3	1	ACCELERATOR ASSEMBLY	1	ASSEMBLY
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99	1	ACCELERATOR ASSEMBLY	1	ASSEMBLY
100	1	ACCELERATOR ASSEMBLY	1	ASSEMBLY

Figure 4. Accelerator assembly drawings

Figure 5. Exploded view of the insulator-column subassembly depicting the alignment sequence.

connecting to the flanges in the insulator column. This is a much more rugged and functional design than that originally proposed.

B. SUBSYSTEM FABRICATION AND ASSEMBLY

1. Arc Chamber

The arc chamber components were machined from OFHC copper without incident. The assembly was furnace brazed with CUSIL. Since the parts were designed to be largely self-jigging, the procedure is straightforward but labor intensive (particularly the repair of any leaks that may occur). The components and final assembly are shown in Figure 7.

The arc chamber components were originally assembled with "C" seals. Although all parts were checked and found to be dimensionally correct, it was impossible to produce a reliable vacuum seal. Contrary to the manufacturer's specifications, we found that the seals did not spring back to their original cross section when removed from the assembly and that they did not achieve even the original level of (unacceptable) performance when reused, even after replating. After several attempts to make the "C" seals work, we received permission from LBL to substitute "O" rings at the seal locations.

The reason for the failure of the "C" seals is not clear, particularly in light of our success with small circular seals of the same type used to seal the water lines from the rail holders to the flanges in the ceramic column. A significant difference between the two applications is that the circular seals are constrained by their holders around their outside diameter and cannot expand in this dimension when compressed. They are, therefore, quite stiff. In contrast, the large rectangular seals have long straight sections which can move and flex when loaded and may therefore be much softer under the normal compression applied when the seal is made. If this speculation does, in fact, describe the failure mechanism, it represents a true defect for rectangular seals of this type. The probe plate is machined from a copper plate and presents no particular manufacturing problems.

M13058

(a)

M13066

(b)

Figure 7. Plasma source components.

M13063

Figure 7(c). Wall electrode assembly.

M13443

(d)

M13444

(e)

Figure 7(d,e). Complete plasma source assembly.

2. Insulator Column

Although there was a considerable delay in delivery, the ceramic sections were of excellent dimensional and structural quality. The titanium flanges were machined to print with a numerically controlled mill.

Initially, we found it very difficult to reproduce the high-quality active metal braze that had been achieved in Phase I between the ceramic and the titanium flange. With the assistance of the LBL technical staff, this problem was finally resolved. Although no specific cause of failure was determined, good brazes were achieved after each step in the process had been carefully reviewed, documented, and rigorously followed. We are confident that this process (summarized in Appendix B) can now be repeated as required.

The several ceramic sections were assembled into the final insulator column by tungsten inert gas welding. The key to the success of this procedure was the use of specially designed water-cooled clamps that both held the components in place and acted as a heat dam to prevent thermal stresses at the braze joint. The entire welding operation took six weeks of calendar time. No leaks were found once the job was complete.

The assembled insulator column components and final assembly are shown in Figure 8. The overall length is 0.05 in. longer than the design length, indicating that the backup rings on the ceramics are not seated against the bottom of the grooves in the flanges. This, in principle, allows the insulator column to compress under load as the titanium flanges, which are brazed to the ceramics, flex. This was measured under varying loads. Under the 1-atm load applied when the source is evacuated, only 0.002 in. overall compression is observed. This is within the allowable tolerances of the assembly.

3. Grid Support Structures (Hats)

Our initial design called for all-molybdenum hat assemblies. The design called for four flat side panels, a cone cut into four quadrants for the tapered corner sections, and an additional panel for the "brim." These parts were to be welded to make the final hat geometry.

Figure 8(a). Brazen insulator section.

M13433

Figure 8(b). Detail of welds on insulator assembly.

M13434

Figure 8(c). Detail of welds on insulator assembly.

M13057

Figure 8(d). Corona rings.

M13445

Figure 8(e). Complete accelerator assembly.

The parts were machined without incident. The parts were electron-beam welded together with full penetration welds. Even though the assemblies were immediately annealed, small stress cracks appeared in the welds. These cracks propagated along the welds as attempts were made to make repairs with the electron beam. Several attempts were made to repair the parts with conventional inert gas welding techniques and filler rod, both at outside vendor facilities and at HRL. This process was finally abandoned when cracks propagated out of the weld joints into the base material.

New parts were made from stainless steel using conventional sheet metal techniques. These assemblies were welded and trimmed to size in our shops at HRL. The procedures are straightforward, and the parts were mechanically sound and reliable. Due to the circumstances under which they were built, these components do not have the high tolerances of the rest of the assemblies and some shims were required in the final assembly (Section 3.C) to achieve the necessary alignment. This deficiency is not inherent in the fabrication technique and can readily be eliminated in future assemblies where adequate fixtures can be used. Typical structures are shown in the next section.

The source mounting plate required no welding and was therefore not changed from its original molybdenum specification.

4. Rails/Rail Holders/Shields

a. Rails

The rails were purchased to size from Thermoelectron Corp. They were of excellent quality as delivered.

b. Rail Holders

The rail holders were machined to print, partly at HRL and partly at an outside vendor's location. The modular slots for the source rails were cut with a Wire Cut Electric Discharge machine, which, in some respects, resembles a miniature bandsaw with a computer-controlled table. This procedure worked well for making complex cuts in a difficult material such as molybdenum.

The assembly was made by screwing the pairs of rail holders to a precision ground plate, inserting the rails into the slots, and

electron-beam welding one end of each rail to the rail holder. Even though care was taken to precisely support the rails during the welding process, we found that some vertical misalignment occurred. This was removed by vacuum firing the assembly with suitable shims and weights to align the rails.

The coolant tubes were bent to shape from annealed molybdenum tubing and electron-beam welded to the rail holders. This procedure was successful. However, as described above, we found that the bends in the molybdenum tubing were very susceptible to microcracks as the assemblies were handled. After consultation with the LBL program manager, we decided to cut the molybdenum tubes off at the ends of the rail holders and to braze on stainless-steel adapters to which stainless-steel water lines could then be welded. Braze was added to the joint between the water line and the rail holder at the same time to improve thermal contact between the coolant tube and the rail holder (and to guard against cracks at the electron-beam welds). Although adapting stainless-steel extensions to the molybdenum cooling lines is a straightforward procedure if done in the proper sequence, it becomes a complicated and time-consuming retrofit to achieve pressure-tight joints without permitting the braze material to plug the cooling lines.

When complete, the individual coolant lines were vacuum checked, flow checked to be sure they were clear, and then pressure checked to 300 psi. Hat and rail assemblies are shown in Figure 9.

c. Shields

The original design called for all shields to be formed from sheet molybdenum. This presented a problem for the gradient and suppressor shields. Tooling was made and several attempts were made to produce satisfactory parts. In every instance, wrinkles were created in the skirts of the shield and the parts were deemed unacceptable. After consultation with LBL personnel, it was agreed that these two shields could be fabricated from stainless steel, which is more readily worked.

We suggest that for the future the shields be redesigned along the lines shown in Figure 10. This design would require a bend in only one direction which can be readily produced in molybdenum.

Figure 9. Rail assemblies prior to final assembly (note electrostatic shield on gradient grid missing from photograph).

Figure 10. Possible modification to shield for suppressor grid.

C. FINAL ACCELERATOR ASSEMBLY AND ALIGNMENT

Once all of the subassemblies were in hand, they were measured and installed in their correct relative positions as described below.

1. Insulator Column

After assembly, the insulator column was measured. The results are shown in Figure 11. Note that the overall height is 9.643 in., which is 0.051 greater than the nominal 9.592. This is because the ceramic backup rings did not seat perfectly in their grooves prior to welding. We decided to accommodate the dimensional variations with shims rather than to machine the assembly to size after welding.

2. Rail/Hat Assemblies

The heights and spacing of the individual rail/rail holder assemblies were checked after welding and stress relieving while the assemblies were still attached to the flat mounting plate. The most extensive check was made on the exit rail assembly, which was the first unit to be completed.

The height and lateral position were each measured at three places on each rail — the center line and at a point 1 in. from each end of the rails. From these data, the data in Table 1 were calculated.

The completed rail assemblies were then mounted on their respective hat assemblies. Each hat assembly was then mounted in the insulator column in turn and the rail positions were measured. The necessary shims were cut and the positions adjusted to assure the spacings and tolerances defined in Figure 12 provided by LBL.

First, the source rail assembly was mounted and the location of the top of the source rails (10 location average) defined with respect to the reference flange as shown in Figure 13. With this position fixed, the required location of the rest of the rails was calculated, as also shown in Figure 13. Each of the other assemblies was then shimmed to these reference points. Where necessary, to accommodate surface variations in these hat assemblies, stainless-steel shims were spot welded to the surface of the hats on which the rail holders are mounted.

	H	H_E	H_G	H_J	H_K	H_P	H_S	③	⑤	⑦
A	9.643	9.167	7.530	.476	.251	9.392	7.538	1.800	5.549	1.639
B	9.643	9.166	7.532	.477	.251	9.392	7.533	1.801	5.548	1.638
C	9.642	9.161	7.530	.481	.250	9.392	7.534	1.800	5.549	1.630
D	9.643	9.160	7.530	.483	.251	9.392	7.534	1.801	5.548	1.627

Figure 11. Insulator column dimensions after assembly.

By:

Date:

[Signature]
1-1P-80

TABLE 1
EXIT RAIL DIMENSIONS
(Preliminary Check)

Vertical (Z) Dimensions

z_{mean} = 0.6433 in. (from surface plate)
 σ_z (standard deviation) = 0.0015 in.
 Maximum deviation = 0.005 in. (rail #23)

Horizontal (X) Dimensions

Δx_{mean} (spacing) = 0.3540 (nom = 0.354)
 $\sigma_{\Delta x}$ (standard deviation) = 0.0019 in.
 Maximum deviation = 0.005 in. (space 22/23)
 σ straightness = 0.001 in.

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TOLERABLE ALIGNMENT ERRORS (MILS - 0.001")

ION CURRENT DENSITY = $0.31 \text{ A/cm}^2 \text{ (D}^+)$

TRANSPARENCY = 0.6

BEAM DIVERGENCE ($\sqrt{2} \theta_{\text{RMS}}$) = 0.53 DEGREES

XDL 765-1717

Figure 12. Alignment error limits for rail assembly - unbracketed numbers are RMS limits in 0.001 in.; bracketed numbers are maximum limits for individual rails in 0.001 in.

Figure 13. Rail positions with respect to source flange.

As described in Section 3.C.1, variations in insulator column length and exit hat dimensions required the mounting modification shown in Figure 14.

The final corner shim dimensions to achieve the desired alignment are given in Table 2.

3. Final Assembly Dimensions

As each hat/rail assembly was installed, a complete set of rail and shield dimensional measurements were taken to define the positions of the individual rails and of the ends of the accelerating apertures as defined by the shields. These measurements were made in the HRL Precision Machine Shop using a standard milling machine equipped with an electronic numerical position indicator. A dial indicator with 0.0001-in. sensitivity was mounted in the chuck of the machine and the table moved to null out the indicator at each location. The position of the table was then displayed to 0.0005 in. and recorded manually. These numerical results were subsequently processed with a computer to provide the statistical data presented in Table 3 and illustrated in Figure 15. These data indicate that the rail straightness is excellent for all rails and that the Z position is better for the source and exit rails than for the gradient and suppressor assemblies. This is due to the fact that the source and exit rails are captured in triangular and round apertures, respectively, which constrain the ends of the rails in both the X and Z directions both during and after welding. The ends of the gradient and suppressor rails lie in rectangular channels milled in the rail holders and are, therefore, more free to move in the Z direction and to twist about their Y axis.

4. Pressure/Vacuum Coolant Line Check

Each individual coolant line was pressure checked with alcohol at 250 psi and with a helium leak detector prior to assembly. Each "C" seal joint was similarly verified as the installation of the hat assemblies progressed. In general, we found that the "C" sealed joints were reliably pressure tight and would pump down with a leak detector but when flooded with helium would show a detectable leak. The

END VIEW

Figure 14. Modification to exit hat mounting plate.

TABLE 2
CORNER SHIM DIMENSIONS
(Inches)

Rail	Corner			
	A	B	C	D
Source	0.006	0.010	0.006	0.010
Gradient	0.116	0.110	0.108	0.116
Suppressor	0.073	0.067	0.071	0.071
Exit	0.020	0.020	0.020	0.043

TABLE 3

RAIL AND SCREEN POSITIONS (see Figure 15; all dimensions in inches)

	Rail Assemblies			
	Source	Gradient	Suppressor	Exit
Rail dimensions				
Nominal/Actual	0.142 x .055	0.118 x .055	0.236 x .180	0.125 dia
Z position (a)				
Nominal	0.0	0.208	0.716	1.028
Actual	0.0	0.204	0.717	1.027
Maximum deviation	0.006	0.009	0.006	0.003
±RMS variation	0.002	0.004	0.005	0.002
X position (b) (transverse)				
Nominal/Actual	0.354	0.354	0.354	0.354
±RMS variation	0.001	0.002	0.002	0.001
Y position (c) (screen aperture)				
Width	3.960	4.028	4.039	N/A

(a) The standard deviation for z-axis position of the plasma, suppressor, and exit rails represent 129 measurements made at the center line and at each edge of the screen aperture on each rail. The data for the gradient grid are for measurements taken at the center line only. The unconstrained ends of the gradient rails are loose in their slots to ~ 0.006 in. in the z-direction, making the end measurements indeterminate to this extent.

(b) Since the rail holders are precision milled, the center-to-center spacing of the rails at the mounting points is precisely 0.354 in. The straightness of each rail in the plane of the rail array was calculated by comparing the position measured at the center line with that on an imaginary line calculated to pass the two measured end points.

(c) The width of the overall beam is defined by the screen aperture on the plasma rail array. The center line of each subsequent screen was aligned with this aperture and measured.

Figure 15. Summary of rail alignment tolerances achieved during final assembly. (Design, see Figure 12; measured, see Table 3).

assembly procedure was modified to lightly coat each seal with Apezion M vacuum grease before assembly. All seals were verified as vacuum tight with this procedure.

5. Voltage Holdoff Check

a. Arc Chamber

Before the filaments were installed, the integrity of the anodized aluminum gaskets was verified first using an ohmmeter and then by applying a 100-V ac signal between corresponding pairs of copper plates separated by the gaskets. This procedure initially disclosed failures in two gaskets. New gaskets were made with a protruding tab which could be used as an electrical contact during the anodizing process. These gaskets were installed and passed the above test.

b. Insulator Assembly

Following installation of the hat/rail assemblies and the internal corona rings, the insulator assembly was highpotted to 5 kV dc across each of the three individual sections (in air). Each section read infinity (10,000 MΩ). No breakdowns were observed on the 20 kV and 80 kV sections. Breakdown began just above 5 kV on the 3 kV sections.

6. Vacuum Checks

The arc chamber was vacuum checked as an assembly using a helium leak detector. As described above, we encountered difficulties using the "C" seals originally specified for this assembly. O rings were substituted, the chamber was assembled, and its vacuum integrity was verified to show no leaks on the 10^{-8} cc/sec scale.

The vacuum integrity of the insulating column was similarly tested and verified. Initial difficulties with the ceramic-to-metal braze were present when the two short end sections of the insulator column were brazed. The joints were mechanically strong but required sealing with VAC SEAL^(R) after the assembly was welded. This assembly also proved leak tight on the 10^{-8} cc/sec scale when the final assembly was tested.

SECTION 4

CONCLUSIONS

As described in the preceding section, the Neutral Beam Source was assembled and factory tested to the contractual specifications. With the exception of slightly larger than specified standard deviations on the Z-positions of the gradient and suppressor rails, all tolerances, vacuum requirements, voltage holdoffs and pressure specifications were met. A number of innovative design and fabrication procedures were implemented and verified and a great deal of practical knowledge was gathered that will be of great value when fabricating future sources.

APPENDIX A

STRESS ANALYSIS

OF

WALL ELECTRODE ASSEMBLY

NEUTRAL BEAM SOURCE

by

H. Fong
Electron Dynamics Division
Torrance, California

ANALYSIS

MODEL

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PREPARED BY

HH FONG

12/7/78

WALL ELECTRODE ASSEMBLY
NEUTRAL BEAM SOURCE

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STRESS ANALYSISOF1096004 WALL ELECTRODE ASSEMBLY

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WALL ELECTRODE ASSEMBLY
NEUTRAL BEAM SOURCEI. INTRODUCTION

THE 1096004 WALL ELECTRODE ASSEMBLY IS PART OF THE 120 KV NEUTRAL BEAM SOURCE. IT CONSISTS OF THESE MAJOR COMPONENTS :

		<u>MATERIAL</u>
1096005	GUSSET (10 OF THEM)	304 CRES
1029841	UPPER FLANGE	304 CRES
1096010	TANK SIDE, WALL ELECTRODE (2)	OFHC COPPER
1096011	TANK END, WALL ELECTRODE (2)	OFHC COPPER
1096012	LOWER FLANGE	OFHC COPPER

THE MATERIAL IS EITHER 304 CRES (CORROSION-RESISTANT STAINLESS STEEL) OR OFHC (OXYGEN-FREE HIGH-CONDUCTIVITY) COPPER. THE PRIMARY STRUCTURAL LOADING IS A DIFFERENTIAL PRESSURE OF 2 ATMOSPHERES, BETWEEN THE SF_6 OUTSIDE AND THE VACUUM INSIDE. THE PURPOSE OF THIS PRELIMINARY STRESS ANALYSIS IS TO VERIFY THE STRUCTURAL INTEGRITY OF THE COMPONENTS UNDER THE PRESSURE LOADING.

II. DESIGN CRITERIAA. FACTOR OF SAFETY

FOR ASSESSING THE STRUCTURAL INTEGRITY OF PRESSURIZED PARTS, IT IS COMMON TO USE A FACTOR OF SAFETY OF AT LEAST 3.0, BETWEEN THE LIMIT AND ULTIMATE LOADS. WE WILL THEREFORE USE :

$$P_{\text{limit}} = 2 \text{ ATM.} \approx 30 \text{ PSI}$$

$$P_{\text{ult}} = 3.0(30) = \underline{\underline{90 \text{ PSI}}} \quad \leftarrow$$

USE OF A FACTOR OF SAFETY ACCOUNTS FOR SUCH UNKNOWN AS : VARIATION IN MATERIAL PROPERTIES, STRESS CONCENTRATION EFFECTS, LOAD FLUCTUATIONS DUE TO SYSTEM DYNAMICS, ETC.

II. DESIGN CRITERIA (CONT'D)B. MATERIAL PROPERTIES

THE REQUIRED MECHANICAL PROPERTIES AND STRENGTH.
ALLOWABLES ARE OBTAINED FROM : (ROOM TEMPERATURE)

304 CRES

REF. 1. MIL-HDBK-5C. METALLIC MATERIALS AND ELEMENTS
FOR AEROSPACE VEHICLE STRUCTURES. 15 SEPT 1976.
TABLE 2.7.1.0 (b)

ULTIMATE TENSILE STRENGTH

$$F_{tu} = 75,000 \text{ PSI}$$

YOUNG'S MODULUS

$$E = 29.0 \times 10^6 \text{ PSI}$$

POISSON'S RATIO

$$\nu = 0.32$$

OFHC COPPER

REF. 2. OFHC COPPER : A SURVEY OF PROPERTIES AND
APPLICATIONS. AMAX, INC, 1974.

$$F_{tu} = 30,000 \text{ PSI}$$

$$E = 17.0 \times 10^6 \text{ PSI}$$

$$\nu = 0.33$$

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III. STRUCTURAL DESCRIPTION

1096004 WALL ELECTRODE ASSEMBLY

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WALL ELECTRODE ASSEMBLY
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IV. STRESS ANALYSISA. 1029841 UPPER FLANGE MATL: 304 CRES

THIS FLANGE IS TAKEN AS A RECTANGULAR PLATE, SIMPLY-SUPPORTED AROUND ALL 4 EDGES, AND UNDER TRANSVERSE PRESSURE LOADING.

THE SUPPORTED DIMENSIONS ARE:

LENGTH $a = 22.0"$	
WIDTH $b = 6.65"$	$\left(\frac{a}{b}\right) = 3.31$

THICKNESS
 $t = 0.313"$

REF. 3. ROARK, R.J. FORMULAS FOR STRESS AND STRAIN.

4TH EDITION. MCGRAW-HILL, 1965. p. 225 CASE 36.

FOR $\left(\frac{a}{b}\right) = 3.31$, THE PARAMETERS. $\beta = 0.722$
 $\alpha = 0.136$

AND THE MAXIMUM STRESS AND DEFLECTION ARE (AT ULTIMATE LOAD):

$$\sigma_{ult} = \frac{\beta p_{ult} b^2}{t^2} = \frac{(0.722)(90)(6.65)^2}{(0.313)^2} = \underline{\underline{29,300 \text{ PSI}}}$$

THE MARGIN OF SAFETY (M.S.) IS THUS:

$$M.S. (ULT.) = \frac{F_{tu}}{\sigma_{ult}} - 1 = \frac{75,000}{29,300} - 1 = \underline{\underline{+1.56}}$$

$$y_{ult} = \frac{\alpha p_{ult} b^4}{Et^3} = \frac{(0.136)(90)(6.65)^4}{(29.0 \times 10^6)(0.313)^3} = \underline{\underline{0.027"}} \quad \text{ok}$$

B. 1096010 TANK SIDE

MATL: OFHC COPPER

$$t = 0.188", a = 20.75", b = 2.062"$$

$$\left(\frac{a}{b}\right) = 10.1 \Rightarrow \beta = 0.750$$

$$\alpha = 0.1421$$

$$\sigma_{ult} = \frac{(0.750)(90)(2.062)^2}{(0.188)^2} = \underline{\underline{8,100 \text{ PSI}}}$$

$$M.S. (ULT.) = \frac{30,000}{8,100} - 1 = \underline{\underline{+2.70}}$$

$$y_{ult} = \frac{(0.1421)(90)(2.062)^4}{(17.0 \times 10^6)(0.188)^3} = \underline{\underline{0.0020"}} \quad \text{ok}$$

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IV. C. 1096011 TANK END

MATL: OFHC COPPER

$$t = 0.188", \quad a = 6.250", \quad b = 2.062"$$

$$\left(\frac{a}{b}\right) = 3.03 \quad \Rightarrow \quad \beta = 0.7134$$

$$\alpha = 0.1335$$

$$\sigma_{ult.} = \frac{(0.7134)(90)(2.062)^2}{(0.188)^2} = \underline{\underline{7,720 \text{ PSI}}}$$

$$M.S. (ULT.) = \frac{30,000}{7,720} - 1 = \underline{\underline{+ 2.89}}$$

$$y_{ult.} = \frac{(0.1335)(90)(2.062)^4}{(17.0 \times 10^6)(0.188)^3} = \underline{\underline{0.0019''}} \quad \text{ok}$$

D. 1096012 LOWER FLANGE

MATL: OFHC COPPER

THE LOWER FLANGE IS NOT LOADED BY PRESSURE TO ANY SIGNIFICANT EXTENT. IT IS ACTUALLY A RECTANGULAR STRIP WHICH GOES AROUND THE 4 SIDES AND IS WELL FASTENED TO THE ADJACENT COMPONENT IN THE NEUTRAL BEAM SOURCE ASSEMBLY BY 28 1096006 CAPTIVE SCREWS. BY INSPECTION, THE LOWER FLANGE IS CONSIDERED ACCEPTABLE.

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WALL ELECTRODE ASSEMBLY
NEUTRAL BEAM SOURCE

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IV. E. 1096005 GUSSET

MATL: 304 CRES

 $t = 0.250"$

ASSUME THAT THE 10 GUSSETS HAVE TO WITHSTAND ALL THE COMPRESSIVE LOADS CAUSED BY THE PRESSURE LOADING ON THE UPPER FLANGE. CHECK A GUSSET FOR BUCKLING.

FROM REF. 3 p. 348 CASE A.4, THE CRITICAL COMPRESSIVE STRESS IS

$$\sigma_{cr} = \frac{K E}{(1 - \nu^2)} \left(\frac{t}{b} \right)^2$$

ASSUME ONLY SHADED AREA
IS EFFECTIVE: $a = 1.812"$, $b = 0.500"$
 $\left(\frac{a}{b} \right) = 3.62 \Rightarrow K = 0.44$

$$\sigma_{cr} = \frac{(0.44)(29.0 \times 10^6)}{[1 - (.32)^2]} \left(\frac{0.250}{0.5} \right)^2 = \underline{\underline{3.55 \times 10^6 \text{ PSI}}}$$

THE TOTAL COMPRESSIVE LOAD P ON ALL 10 GUSSETS DUE TO PRESSURE LOADING ON THE UPPER FLANGE IS

$$P = p_{\text{eff}} A = (90)(23.5)(3.25) = 17,500 \text{ LB.}$$

ON EACH GUSSET, THE COMPRESSIVE LOAD IS

$$P_1 = \frac{17,500}{10} = 1,750 \text{ LB.}$$

WHICH CAUSES A COMPRESSIVE STRESS IN THE GUSSET OF

$$\sigma_c = \frac{1,750}{(.25 \times .50)} = \underline{\underline{14,000 \text{ PSI}}}$$

THEREFORE, THE MARGIN OF SAFETY AGAINST GUSSET BUCKLING IS

$$M.S. (\text{BUCKLING}) = \frac{3.55 \times 10^6}{1.4 \times 10^4} - 1 = \underline{\underline{+ \text{HIGH}}}$$

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PREPARED BY

H. H. FONG

12/1/58

WALL ELECTRODE ASSEMBLY
NEUTRAL BEAM SOURCE

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V. MARGIN-OF-SAFETY SUMMARY

RESULTS OF THIS PRELIMINARY STRESS ANALYSIS SHOW THAT STRESSES (AND DEFLECTIONS) IN THE WALL ELECTRODE ASSEMBLY ARE ACCEPTABLE, AND ALL MARGINS OF SAFETY ARE POSITIVE FOR THE ASSUMED PRESSURE LOADING.

COMPONENT		M.S.
1029841	UPPER FLANGE	+1.56
1096010	TANK SIDE	+2.70
1096011	TANK END	+2.89
1096012	LOWER FLANGE	+HIGH
1096005	GUSSET	+HIGH

APPENDIX B

PREPARATION AND BRAZING PROCEDURES

FOR

NEUTRAL BEAM SOURCE

CERAMIC INSULATOR ASSEMBLIES

**HUGHES
RESEARCH LABORATORIES**
MALIBU, CALIFORNIA

SPECIFICATION NO. HVT-AP-031

PREPARED BY	PAGE	OF
Paul W. Sumner	1	4

SPECIFICATION TITLE
PREPARATION AND BRAZING PROCEDURES
FOR
NEUTRAL BEAM SOURCE
CERAMIC INSULATOR ASSEMBLIES

APPROVALS			DATE	REV
<i>[Signature]</i>				

MATERIALS:

Ceramics: HRL P/N D1029832-1 through -3
WESGO's AL-500 Alumina (94%) or equivalent

Braze Alloy: WESGO's Ticusil Foil .003"
Ag-Cu-Ti or equivalent

Titanium Flange: HRL P/N D1029859
Commercially pure grades 2-4 or equivalent

I. CERAMIC PREPARATION

- A. Chamfer edges.
- B. All ceramics to be cleaned per HRL Specification Number IPD-PR-016. (Omit steps 1, 2, and 3 which pertain to dirty parts.)

(NOTE) Handle ceramics at this time only with white cloth or plastic gloves.
- C. Air-fire at 1000°C for one hour at a temperature heating rate not to exceed 5°C/min. on heating, slow cool to room temperature. Surfaces of ceramics to be coated with alumina powder on surfaces with ceramic rods used to separate each ceramic during firing.

II. BRAZE ALLOY PREPARATION

- A. Cut foil to shape.
- B. Remove surface oxides by sanding with (alumina oxide) 400 grit paper.
- C. Rinse with ethyl alcohol (Regent Grade) place in 100°C oven to dry.
- D. Place in clean plastic containers until ready for use.

(NOTE) Sanding should be accomplished within 24-48 hours prior to brazing to prevent oxides from forming again.

III. TITANIUM FLANGES

- A. All titanium to be cleaned per HRL Specification Number IPD-PR-017.
- B. Place in clean plastic containers until ready for use.

(NOTE) Cleaning of titanium should be accomplished 24-48 hours prior to brazing to prevent oxides from forming.

IV. TOOLS USED IN BRAZING

- A. Flat ground plate steel, titanium or ceramic.
- B. Slip plate (to be used between flat plate and insulator stack) to be a small insulator ceramic. HRL P/N D1029832-2 or equivalent.
- C. Locating blocks, stainless steel machined slotted blocks with set screws. These blocks slip over titanium flanges to insure proper alignment between flanges and insulators. NBS sketch #101.
- D. Weights used for 140 lbs needed on insulator stack during brazing run, are random sizes, either made of tungsten, molybdenum, or kovar, rod, bar and/or plate stock.
- E. Heat shield consisting of a frame and outer metal sheet to completely cover insulator stack on all sides and top during brazing run. Shield to be made of either titanium with a tantalum liner (to shield insulator stack from titanium) or completely made of tantalum.

V. SET FOR BRAZING

- A. Spot weld ticusil braze foil to titanium flanges.
- B. Clean fire braze oven 1000°C one hour.
- C. All tooling to be acid cleaned and solvent washed prior to brazing.
- D. A short ceramic (slip plate) shall be used as a divider between steel flat plate and braze set-up.
- E. A shield of tantalum sheet or foil shall be used to prevent exposure of titanium to insulator stack during brazing.
- F. Thermocouples shall be placed as follows:

1. Two thermocouples attached to braze flanges on interior of insulator stack.
 2. Two thermocouples attached to braze flanges on exterior of insulator stack.
- G. 140 pounds of weight shall be applied to insulator stack distributed uniformly across upper member.

VI. SET-UP OF INSULATOR STACK FOR BRAZING

- A. Have all materials needed, cleaned, bagged and ready for use; parts and all details to be handled with clean white cloth and/or plastic gloves.
- B. Place flat plate on loading platform of braze furnace.
- C. Add slip plate.
- D. Place one (1) HRL P/N D1029832-1 backup ceramic on slip plate.
- E. Locate one (1) HRL P/N D1029859 titanium flange onto backup ceramic. Titanium flange shall at this time already have titanium braze alloy foil spot welded onto it, and also have the stainless steel locating blocks set in place.
- F. Next place one (1) HRL P/N D1029832-2 or -3 ceramic on top of titanium flange.
- G. Follow with another one (1) HRL P/N D1029859 titanium flange; and next with one (1) HRL P/N D1029832-1 backup ceramic.
- H. After all ceramics and titanium flanges have been set in place, apply 140 lbs of weight spaced evenly around complete top of insulator stack.
- I. Install two (2) thermocouples to interior sections of titanium flanges, and two (2) thermocouples to exterior sections of flanges. These thermocouples can be fastened in place using nickle ribbon and spot weld onto the titanium flanges.
- J. Place heat shield over insulator stack assembly and place tantalum foil between titanium and ceramic stack if required.
- K. Load ceramic insulator stack assembly into vacuum braze chamber and prepare for braze run.

VII. BRAZING RUN

- A. During the run, plot the temperature versus time and aim at a 3-hour heatup time which corresponds to a rate of $550^{\circ}\text{F}/288^{\circ}\text{C}$ per hour. The temperature differences between all thermocouples must not exceed $90^{\circ}\text{F}/32^{\circ}\text{C}$. The temperature referred to in this brazing schedule is measured at the coldest thermocouple; all others to be within $90^{\circ}\text{F}/32^{\circ}\text{C}$.
- B. Evacuate furnace to Pressure $\leq 8 \times 10^{-4}$ Torr before applying any heat.
- C. Heat from ambient to $575^{\circ}\text{F}/302^{\circ}\text{C}$ at a rate less than $550^{\circ}\text{F}/288^{\circ}\text{C}$ per hour ($9^{\circ}\text{F}/5^{\circ}\text{C}$ per min.).
- D. Hold temperature at $575^{\circ}\text{F}/302^{\circ}\text{C}$ for 60 minutes or less until pressure is $P \leq 1 \times 10^{-4}$.
- E. Heat from $575^{\circ}\text{F}/302^{\circ}\text{C}$ to $1450^{\circ}\text{F}/788^{\circ}\text{C}$ at a rate less than $550^{\circ}\text{F}/288^{\circ}\text{C}$ per hour.
- F. Hold temperature at $1450^{\circ}\text{F}/788^{\circ}\text{C}$ for 30 minutes.
- G. Heat from $1450^{\circ}\text{F}/788^{\circ}\text{C}$ to $1625^{\circ}\text{F}/885^{\circ}\text{C}$ at a rate less than $550^{\circ}\text{F}/288^{\circ}\text{C}$ per hour.
- H. Hold at $1625^{\circ}\text{F}/885^{\circ}\text{C}$ for 10 minutes.
- I. Cool to $1110^{\circ}\text{F}/599^{\circ}\text{C}$ at less than $550^{\circ}\text{F}/288^{\circ}\text{C}$ per hour and hold for one-half hour.
- J. Cool to $885^{\circ}\text{F}/474^{\circ}\text{C}$ at less than $550^{\circ}\text{F}/288^{\circ}\text{C}$ per hour and hold for two hours.
- K. Cool to room temperature at less than $550^{\circ}\text{F}/288^{\circ}\text{C}$ per hour.

NOTE: Argon gas can be used to accelerate cooling rate to $550^{\circ}\text{F}/288^{\circ}\text{C}$ per hour if temperature is below $350^{\circ}\text{F}/177^{\circ}\text{C}$.

Rev. 8

HUGHES RESEARCH LABORATORIES MALIBU, CALIFORNIA	SPECIFICATION NO. IPD-PR-016		
	PREPARED BY W. Perkins	PAGE 1	OF 1
SPECIFICATION TITLE GENERAL CLEANING OF CERAMIC PARTS	APPROVALS		DATE REV
<p>MATERIALS</p> <ol style="list-style-type: none"> 1) Ethyl Alcohol 2) De-ionized or distilled water 3) Solution of 85% H_2SO_4 ---15% HNO_3 <p>EQUIPMENT</p> <ol style="list-style-type: none"> 1) Sand Blaster (Optional) 2) Basket or holder for parts 3) Appropriate beakers or containers for parts 4) Air firing furnace 5) Thermometer (capable of 250 °C) <p>PROCEDURE</p> <ol style="list-style-type: none"> 1) Very dirty or heavily coated parts should be degreased per IPD-PR-010 and then grit blasted with powder (Wall Colmonov Al_2O_3 PSM 434). 2) Immerse in boiling (125 - 150 °C) H_2SO_4/HNO_3 solution for 5 - 10 minutes. (Repeat if necessary to remove metal) 3) Rinse thoroughly in running distilled or de-ionized water 4) Rinse twice in boiling de-ionized water or in two successive ultrasonic cleanings of not less than 5 minutes. 5) Rinse in alcohol and air dry parts at 120 °C $\pm$ 10 °C. 6) Store parts in clean covered containers. <p>PRECAUTIONS</p> <ol style="list-style-type: none"> 1) The acid bath is very corrosive. DO NOT HEAT OVER 200 °C. If spilled wash away immediately with large quantities of water and/or neutralize with soda ash and water. Wear protective clothing and eye protection. 2) To minimize possibility of cracking ceramics, do not heat or cool parts at a rapid rate. 			

Revision A

HUGHES RESEARCH LABORATORIES MALIBU, CALIFORNIA	SPECIFICATION NO. IPD-PR-017										
	PREPARED BY Ross D. Olney	PAGE 1	OF 2								
SPECIFICATION TITLE Bright Dipping Titanium Procedure	APPROVALS		DATE REV								
<div data-bbox="272 716 402 747">1. <u>SCOPE</u></div> <div data-bbox="334 747 1308 821">1.1 This specification establishes the procedure for bright dipping of titanium parts before assembly or subsequent welding operations.</div> <div data-bbox="272 835 488 867">2. <u>REQUIREMENTS</u></div> <div data-bbox="334 884 513 915">2.1 <u>Materials</u></div> <div data-bbox="394 930 695 1108"> 2.1.1 Oakite #90 2.1.2 Sulfuric acid 2.1.3 Nitric acid 2.1.4 Hydrofluoric acid 2.1.5 D.I. water </div> <div data-bbox="334 1125 516 1157">2.2 <u>Equipment</u></div> <div data-bbox="394 1171 732 1314"> 2.2.1 Stainless steel tank 2.2.2 Polypropylene tank 2.2.3 Rinse tank 2.2.4 Imersion heater </div> <div data-bbox="280 1331 444 1362">3. <u>PROCEDURE</u></div> <div data-bbox="339 1367 1304 1440">3.1 Make solution of Oakite #90 in polypropylene tank at 60-80 grams per liter depending on how big parts are. Use at 80°-90° C via imersion heater.</div> <div data-bbox="339 1434 1062 1472">3.2 Make solution of bright dip in stainless steel tank at</div> <div data-bbox="651 1482 932 1625"> <table> <tr><td>D.I water</td><td>22%</td></tr> <tr><td>Nitric acid</td><td>22%</td></tr> <tr><td>Sulfuric acid</td><td>52%</td></tr> <tr><td>Hydrofluoric acid</td><td>4%</td></tr> </table> </div> <div data-bbox="402 1633 1295 1703">by volume. <u>These must be mixed in this order.</u> Addition of sulfuric acid will cause temperature to rapidly rise about 100°C. Add <u>very</u> slowly.</div> <div data-bbox="344 1696 1321 1808">3.3 Oakite #90 is a cleaning solution. Place part to be dipped in this solution for 1 to 5 minutes depending upon necessity. Oakite #90 solution cleans parts of dirt and fingerprints, so they must now be handled very carefully. Tongs or rubber gloves must be used.</div>				D.I water	22%	Nitric acid	22%	Sulfuric acid	52%	Hydrofluoric acid	4%
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- 3.4 Rinse parts free from any Oakite #90 solution in running water.
- 3.5 Place parts in bright dip solution for desired length of time (probably 10 sec. to 2 min.). Removal rate at 60°C is 0.0002 inches per minute.
- 3.6 Rinse parts in D. I. water.
- 3.7 Rinse parts in acetone, let dry.
- 3.8 Place parts in clean plastic bags.

4. PRECAUTIONS

- 4.1 Parts should be mechanically clean and free of heavy deposits of grease, dirt, etc., before starting the above procedure.
- 4.2 Clean parts should be handled only with tweezers or with clean gloves, never with fingers.
- 4.3 Acid solution should last approx. 3 months with proper care.

5. SAFETY

- 5.1 Avoid prolonged or repeated breathing of acetone vapors. Acetone is highly flammable. Observe fire precautions.
- 5.2 Solution is corrosive. In case of spillage, wash away immediately with lots of water.
- 5.3 There are Hughes Products Safety Bulletins that describe the precautions necessary when handling these acids. The following are mandatory.

- 1) Rubber gloves
- 2) Goggles or face shield
- 3) Rubber or plastic apron

NOTE:

DO NOT DEVIATE FROM THE ABOVE PROCEDURE. TITANIUM THAT HAS BEEN EXPOSED TO TRICHLOROETHYLENE, METHOL ALCOHOL OR ACID FROM FINGERPRINTS EASILY FRACTURES DUE TO STRESS CORROSION CRACKING UNDER CERTAIN STRESS CONDITIONS.