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PRELIMINARY DESIGN OF A MAGNETOHYDRODYNAMIC (MHD)
CHANNEL FOR THE U. S. S. R. U-25 FACILITY

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ABSTRACT

This report portrays the results of the preliminary design effort for a magnetohydrodynamic (MHD) channel for the U.S.S.R. U-25 facility. It also delineates the design and engineering effort required to make this channel compatible with the High Performance Demonstration Facility (HPDF) located at the Arnold Engineering Development Center, Arnold Air Force Station, Tennessee. The channel is of a variable wall angle, single output, windowframe design. This preliminary design provides a departure point from which both detail design and construction may proceed concurrently. A detailed program plan and schedule for the final design, construction and proof testing of the channel at the HPDF and U-25 facilities is included.

SECTION I
INTRODUCTION

1.0 INTRODUCTION

1.1 General Information

Contract Number OCR 14-32-0001-1733 was awarded by the Department of the Interior, Office of Coal Research to MEPPSCO, Incorporated of Boston, Massachusetts effective 13 May 1974.

The objective of this Program was to conduct a preliminary design for a magnetohydrodynamic (MHD) channel system to be installed and operated at the Soviet U-25 facility in Moscow. This channel system was to be designed for a continuous operation time of not less than 100 hours, and was also to be compatible with the U.S. High Performance Demonstration Facility (HPDF) located at the Arnold Engineering Development Center (AEDC), Arnold Air Force Station, Tullahoma, Tennessee.

For those readers who may be interested more in the overall aspects of the U-25 program as well as the Program Plan and Cost Estimate, this fairly detailed Introduction together with Section IV - Program Plan and Schedule, and separate Section V - Cost Estimate may be read separately.

1.2 Background Data

Under a previous OCR Contract, Number 14-32-0001-1541, MEPPSCO participated in the Ad Hoc Working Group for the preparation of a conceptual design for a U.S. channel to be tested in the Soviet U-25 MHD plan. On 27 November 1973 in Washington, MEPPSCO presented its initial thoughts on a conceptual design to the Soviet working group and other members of the U.S. working group.

The concept of a single output, windowframe diagonal channel was selected by MEPPSCO in spite of its modest performance under U-25 operating conditions. This selection was based on the conviction that there is a critical necessity for the entire development of MHD to arrive at reliable channel configurations which can be coupled to the power grid through realizable, reliable, and economically feasible inverter systems. During that presentation, we demonstrated the expectation that the modest reduction in MHD performance due to a single load should be amply compensated for by inverter cost reduction and improved reliability. Additionally, with single output, the reliability of the MHD channel itself should be much improved due to removal of the pressure to coarsen the segmentation (and increase inter-element voltages) so as to reduce the number of individual output circuits with a multiple output configuration. It was our impression that these conclusions were endorsed by the Soviet delegation based upon their unique experience with the complex U-25 inverter system.

Through the Working Group Sessions in Moscow February 18-21, 1974 MEPPSCO continued to examine this conceptual design. Our conceptual investigations indicated that:

- A. The channel should exhibit a power output of ten (10) Megawatts or more with the conductivities expected for the U-25.
- B. With additional design provisions, the channel and its associated equipment could be compatible with both the U-25 and the magnet to be utilized for the High Performance Demonstration Facility (HPDF) if the option of continuous room temperature water cooling for that magnet was provided. A new combustion chamber designed to operate at the lower pressure appropriate to the U-25 would be required. Other more modest modifications to the configuration of the HPDF would increase run duration and permit injection of electrode maintenance materials.
- C. The design would operate with modest electric field levels over the major portion of its length. Therefore, the U-25 program should be most valuable for a basic mechanical-cooling-examination of the large long duration, variable wall angle single output windowframe design. Additionally, the program would demonstrate proper adjustment of the power takeoff to avoid excessive field level, current concentration and losses in the channel ends and for a comparison of single output performance under realistic power takeoff and load conditions with the ideal Faraday design.

MEPPSCO provided load specifications for the conceptual design at the working group sessions in Moscow February 18-21, 1974. These load specifications were discussed with the Soviet side, and easy compatibility with the U-25 power conditioning equipment was demonstrated. In fact, due to the single output, much of the U-25 inverter system would not be required, and would be available for on-line adjustment of the power takeoff position with the MEPPSCO design.

The Preliminary Design Program, which is the subject of the final report, has carried the program to the point where detail design and construction of the U-25 channel system can begin. With a sound Preliminary Design now available, we believe that detail design and construction can and should proceed concurrently.

Three (3) methods for construction of diagonal MHD channels were considered:

- A. Mosaic element insulating wall with the diagonalization effected by external connections. In this construction, the channel cross section is a rectangular built up of four walls on which the electrode and insulating wall elements are mounted. These walls are then joined and sealed together to form a pressure vessel. This construction is currently employed for the short duration MHD channel LP-2 being designed by MEPPSCO for the High Performance Duration Experiment at the Arnold Engineering Development Center. Because the insulating wall is finely divided and the electric field can have arbitrary orientation, this geometry provides maximum flexibility in the arrangement of the diagonal connections.
- B. Insulating walls composed of diagonal members mounted on glass reinforced plastic and in contact with the gas but with external (or at least away from the gas surface) connection between the diagonal elements and the electrode wall. The rectangular box pressure vessel construction is as (A) above.
- C. Window frames with variable wall angle and cooling integral with the individual frames.

For a channel intended for long duration operation, and particularly one of the size appropriate to the U-25, the integrity of the cooling system is considered to be the most important construction feature. This alone forced rejection of the mosaic-type of insulating wall construction. It has been demonstrated that the cooling integrity of the mosaic type of insulating wall construction cannot be assured. The choice between the box-type and windowframe configuration was determined by:

- A. The number of times that the channel pressure vessel is pierced should be held to an absolute minimum.
- B. The efficient utilization of magnet aperture by the windowframe permitting easy compatibility with both the U-25 and AEDC magnets.
- C. Traditional difficulty with scouring, condensation, and shorting in the joint area between the four walls in the box-type construction.

- D. The fact that the apparent flexibility of the box-type construction with regard to diagonalization is more imagined than real, since the potential difference that can be tolerated between the end of a diagonal element and an adjacent electrode element is limited.
- E. A special feature in this case is the ease of extending the length of the windowframe channel to provide compatibility with the AEDC magnet which is slightly longer than the U-25 magnet.
- F. Excellent mechanical and cooling experience with the large LORHO Pilot and Scale Long Duration Windowframe Channels operated in the 1960's. These channels utilized external coolant manifolding and integral individual windowframe cooling as in the current U-25 design.

1.3 Summary

The windowframe construction of the diagonal conducting wall (DCW) generator is not a new concept. The channels employed by the workers at UTSI, and the long duration Hall channels used in the mid-1960's were of windowframe construction. The largest MHD generator in terms of volume, the circular 18,000 Kilowatt LORHO Pilot Hall generator is another example of the use of windowframe construction. The record of cooling system integrity for this construction is impressive.

The use of variable wall angle for this design is believed to be a new application of the windowframe construction. With variable wall angle:

- A. Wall angle variation can be programmed to "track" desirable operating conditions over the length of the generator through a wide variation of pressure and Hall coefficient.
- B. Permits easy interfacing of the channel with diffuser and nozzle.
- C. Reduces the volume involved in power takeoff, and allows power takeoff to be achieved at moderate wall angle.
- D. Permits satisfaction of diagonalization conditions on the electric field while retaining control of channel aspect ratio.

Section II describes the design performance analysis of the variable wall angle windowframe design. An important part of this analysis is the effect and inclusion of mechanical and electrical constraints imposed by the method of construction. Since the frames are in mechanical contact with each other, and wall angle variation is achieved by tapering the frames, the relationship between the parameters of frame taper and the rate of wall angle variation is derived.

When practical values for the taper parameters are utilized, it is found that the rate of wall angle variation in the channel ends must be constrained to somewhat less than the most desirable value from other considerations. In particular, this constraint results in the nozzle-channel interface being inclined at an angle of 18° to the normal to the flow. However, the diffuser-channel interface can be normal to the flow. An important corollary to the constraint is that it is essential to specify the variation of wall angle rather than derive it in order to achieve a design that can actually be constructed.

The other constraint imposed by the construction is electrical, that is since the frames are equipotentials as well as in mechanical contact, the electric field must satisfy certain conditions. These are also derived in Section II with the result that, to first order, away from the fringe field:

$$V_T = \text{constant}$$

where V_T is the transverse (Faraday) voltage. Both the mechanical and electrical constraints are applied to the design analysis.

Available computer programs are utilized to produce a channel gas side loft compatible with both the U-25 and AEDC-HPDE magnets at a flow of fifty (50) Kilograms/second. The two gas side lofts are shown in Figs. 1-1 and 1-2. A computer program to design the frames given the channel parameters was written and checked out.

During the program, MEPPSCO has been fortunate to have worked closely with STD Research, Inc. (STD) who have carried out detailed performance analysis of the design. Drs. Craig Maxwell and Ahmed Kassem have carried out the work at STD. STD has participated as an independent OCR contractor, and has not been under contract to MEPPSCO. Table 1.3 shows the design point, and Fig. 1-3 shows the V-I characteristics predicted by STD. Further material supplied by STD relative to these calculations is included in Appendix 3.

Fig. 1-1. U-25 SOD Channel

Fig. 1-2. U-25 SOD Channel in AEDC Magnet

Fig. 40. Typical output current-voltage characteristics for the MEPPSCO U-25 Revision 5 design operating at 50 kg/s with inlet conductivity $\sigma \approx 9.8 \text{ mho/m}$.

STD-74-0442

STD RESEARCH CORPORATION

Fig. 1-3. The Output Characteristic of the MEPPSCO U-25 SOD Channel in the Diagonal Mode

TABLE 1.3-1

50 KG/SEC, REVISION 6

	<u>STD</u>
Current	3250
Voltage	4700
Power Output	15.5
Conductivity (Inlet)	9.8

Max. Conductivity - 12.5 Mho/m

Section III contains the preliminary mechanical analysis and design of the windowframe channel system. It is believed that the material presented here provides a conclusive demonstration of the mechanical feasibility of the design.

The MEPPSCO basic design philosophy for a large MHD generator is very simple:

- A. Protect the channel cooling system from exposure to hot gases and provide adequate cooling via forced convection for the worst case eventuality.
- B. Interpose the cooling system between the hot gases and the load bearing structure and seals.

When these two axioms are followed, the likelihood of a serious failure leading to escape of hot gases is minimal. The great advantages of the windowframe construction in providing these features, and the record of integrity for this construction is the basic reason for its selection along with the efficient use of magnet aperture. The Section includes a detailed worst case cooling system analysis of the three components (nozzle, channel, diffuser) assuming cold walls, and that all of the boundary layer electrical dissipation appears as wall heat load. On the basis of this analysis, increase in coolant flow rate over that provided by the original U-25 specifications was requested and has been provided by the Soviet side. The Section also contains semi-detailed stress analysis of the components. It is shown that the loads are not critical and that, in particular, silver bearing copper may be used for the channel frames with brazed on Inconel for the electrode structure. The use of copper leads to excellent cooling system integrity even with the complete failure of the electrode system, and loss of the Inconel electrodes themselves.

An important aspect of the Program is to provide compatibility with the AEDC-HPDE facility. The thin walls of the windowframe construction permit this compatibility to be provided at a flow rate of fifty (50) Kilograms/second, fully meeting the OCR specifications. Figures 1-4 and 1-5 are the compatibility drawings for U-25 and AEDC facilities. Figure 1-6 is an artist's conception of the channel installed in the U-25 magnet but prior to installation of the top coil and pole. Section III has also given detailed attention to the interfaces between the U-25 facility and the U.S. equipment.

The electrode system is discussed in Section 3.6. The channel design is flexible as to the precise electrode configuration to be employed since the electrode structure itself is furnace brazed to the frame inside the coolant passage. At the beginning of the Preliminary Design Program, our intent was to utilize an electrode system more or less identical to those utilized for long duration tests in the mid-1960's⁽¹⁾. This system utilized a magnesia insulator with a zirconia based electrode. In situ maintenance via addition of zircon and natural magnesite was utilized to sustain and seal the gas surface. With small channels, single tests of up to two hundred (200) hours, and total lifetimes of several hundred hours were achieved.

The basic discussion in Section 3.6 is centered on the use of such a system with MgO insulator and maintenance by zircon and magnesite. However, we would like to retain the option of utilizing a potentially attractive system that has recently been proposed should this system prove to be attractive after test in a generating situation. This is the system based on hercynite ($FeAl_2O_4$)⁽²⁾ with the conducting-insulating property adjusted by excess-lean FeO concentration. Surface temperature of $1700-1800^{\circ}C$ would result. With this system, the insulator would be alumina and the maintenance material would be $FeO + Al_2O_3$ with adjusted excess FeO to impart conductivity. The system has the advantage of relatively uniform conductivity over a wide temperature range, and would permit the use of a relatively low temperature iron-ceramic interface and insulator; the main question with this system seems to be whether the viscosity will be high enough to achieve acceptable feed rates.

A crucial aspect of the Final Design Program (described in Section IV) is the design, assembly and test of a small MHD channel to verify the in situ electrode system maintenance methods which will be employed. This channel will be operated at an existing MHD test facility.

Section IV provides the Program Plan and schedule for the U-25 Program. PERT-type charts for the U-25 Master Schedule and Final Design Schedule are given. Important milestones in these schedules are:

Fig. 1-6. Artist's Concept of Channel in U-25 Magnet

Inception	Commence final design Begin required modification to AEDC facility
Month 13	Begin pre-shipment checkout at AEDC
Month 19	Begin test at U-25

The schedules have been prepared on the basis of phased concurrency of the Final Design and Fabrication process and assumes a continuous Technical Directive (TD) project review and monitoring process.

In order to reap maximum benefit from the U-25 program, MEPPSCO strongly recommends that OCR consider fabrication of two (2) identical channel systems. The first channel would be scheduled for initial test under U-25 type conditions at AEDC as shown above, but would be committed to a lengthy and thorough test program at AEDC rather than a short pre-shipment test. The second channel would go directly to test at the U-25. Early test results with the first channel at AEDC could be incorporated into the final fabrication of the second as required. After completion of the second channel, the first channel would be subjected to a lengthy test program at AEDC at high fields (4T) for periods of up to one (1) hour with the test conditions closely simulating the downstream section of a U.S. base load plant. The second channel would be run for extended duration in the U-25 facility.

Section IV has also considered preliminary field organization and manpower requirements which total seventeen (17) personnel of all categories headed by a U-25 Technical Field Director reporting directly to OCR. A preliminary layout of a 30' x 60' shop and assembly area which would be required is presented. Finally, field instrumentation, data logging and computation requirements are discussed. It is recommended that OCR consider the use of a stand-alone mini-computer based system based on a real time FORTRAN as the most efficient and cost effective means for accomplishing these functions. The system could be completely checked out at AEDC and simply plugged in for the test program at Moscow.

Section V under separate cover, provides an overall cost estimate for the U-25 program.

1.4 Conclusions

In spite of the fact that the magnetic field level is somewhat less than optimum, the Soviet U-25 MHD facility is unique in the entire world for its ability to support the test of large MHD channel systems for extended periods.

No U.S. facility to provide extended duration test capability for a channel of the size of the U-25 on Category A fuels will be ready for at least six (6) years after the beginning of the test period in the U-25. The U-25 facility is probably valued at well in excess of \$100,000,000 and is staffed with experienced operators who have already solved many of the practical problems of operating an MHD plant. In the opinion of MEPPSCO, the opportunity to achieve extended duration test of a channel system of this size in the time scale and for the dollars involved is a pretty fair bargain.

The single output, variable wall angle, windowframe diagonal (SOD-DCW) design provided by MEPPSCO will represent a substantial advance in the state-of-the-art in MHD both with regard to channel system design as well as in practical coupling of the MHD output to the power system. The basic coolant and structural integrity of the design is believed to be sound, and the design is self-protecting against a serious failure that would allow escape of hot working fluid. The modest electric field levels lead to relatively low interelement potentials which should provide high probability for achieving the desired life--but that is what this is all about. The design substantially exceeds the minimum OCR performance requirements, and is fully compatible with both the U-25 and AEDC facilities. The Program Plan indicates that initial operation of the U.S. system in the U-25 can commence nineteen (19) months after inception of Final Design.

During the course of this Preliminary Design, as well as previously, MEPPSCO has, through OCR, worked closely with Soviet-MHD workers concerned with both the scientific and engineering aspects of the U-25. In these contacts, we have always experienced the complete cooperation of our partners in the cooperative program; forthright, sometimes tough and exacting discussion that solves problems and invites respect. Should this design be received favorably by OCR, we look forward to continued cooperation of the type that has always characterized relations between Soviet and U.S. MHD workers.

SECTION II

DESIGN PERFORMANCE ANALYSIS

2.0 DESIGN PERFORMANCE ANALYSIS OF THE U-25 SOD CHANNEL

2.1 Introduction

The purpose of the design flow analysis is to prepare a tentative gas side loft of the MHD channel as well as a wall angle distribution. The gas side loft can then be used as the basis for mechanical design of the channel as well as off design examination of the performance under varying load conditions and departure of operating conditions (conductivity, Hall coefficient, electrode temperature, wall roughness, etc.) from those which have been assumed in the design flow analysis.

Thus, there is a basic difference between the design and off design analysis. The purpose of the design analysis is to create something for everyone to work with and update as the design proceeds. In the design analysis, the channel designer attempts to meet the performance specifications and at the same time take into account all of the other constraints which are imposed. In the case of the U-25 channel, these constraints may be summarized:

- A. Performance characteristics of the U-25 gas generator
- B. U-25 magnetic field
- C. Power conditioning equipment specifications
- D. Coolant supply specifications
- E. Nozzle and diffuser interface specifications
- F. Mechanical constraints on form of wall angle variation
- G. Dual compatibility with AEDC HPDF magnet

We have selected a subsonic accelerating flow with a choked exit. Such a flow will exhibit excellent stability for both inviscid core and boundary layer. As long as there is conductivity margin (as is the case with this design) the desired flow condition can be produced in spite of departure of such effects as electrode drop from expected or assumed values by substantial margins. In addition, the subsonic flow situation is the one of most interest for the base load, coal fired MHD plants which are the primary interest of OCR. The subsonic flow is not without disadvantages. The inlet Hall coefficient is low due to the low value of field strength in the U-25. Since the wall angle at the inlet is limited by both mechanical and electrical considerations, the local turbine efficiency is low throughout the generator; this is partly compensated for by the reduced end effect losses at low efficiency. The reduced efficiency also eases the power takeoff problems and likelihood of arcing. Additionally, a low turbine efficiency leads to

low wall angle at the downstream end of the channel and so reduces the volume involved in power takeoff where the Hall coefficient is maximum. Finally with the 4T field which can be produced at AEDC, the efficiency will be much improved.

In addition to the above, a supersonic design was rejected because:

- A. Due to the low pressure ratio of the U-25, a low and probably decelerating supersonic flow with a design exit Mach number of 1.2-1.3 would be required. We consider that the probability of mid-channel shocks with flow separation and high electrical losses with a diagonal design is high in this situation. The performance penalty for such discontinuities in a single output generator will be substantially greater than in a Faraday with separately loaded electrodes.
- B. An efficient supersonic diffuser design is difficult with the space available at the U-25, unless the option of extending the diffuser into the steam generator is utilized. We do not favor this option because of the rectangular-round transition that would be required, and the fact that the higher heat losses with the longer diffuser will increase cooling water requirements.

The flow flexibility available to the designer is not great. For the design inlet conditions, velocity, gradient, current, conductivity, and wall angle distribution can be varied somewhat. The greater the velocity gradient the higher the inlet pressure; the lower the Hall coefficient and the lower the inlet efficiency. Mechanical and electrical considerations limit the inlet wall angle to $\phi \approx 1.2$. Thus, the designer is restricted in his choice of inlet conditions.

2.2 Constraints

The United States channel must be designed to the specifications of the U-25 facility. The initial specifications were provided by the Soviet side in July 1973.⁽³⁾ The Soviet side subsequently provided drawings illustrating detailed features of the U-25 installation. During the preliminary design process, certain modifications and clarifications of the Soviet specifications have been requested by MEPPSCO. Additionally at meetings with the Soviet side in Washington, D.C. on 22 October 1974, significant modifications of the specifications were provided to increase the maximum steady flow capability of the U-25 installation by 10%. Correspondence regarding these matters is contained in Appendix 1.

The constraints and specifications are discussed here because they have a profound influence on the design performance analysis.

2.2.1 U-25 Gas Generator. In spite of the fact that the combustion pressure is somewhat lower than we would consider optimum for an MHD installation with a high field strength magnet like the AEDC High Performance Facility, the U-25 gas generator at the present time must be considered without par in the entire world for the combination of flow rate, preheat capability and oxygen enrichment that it presents. With the successful development of combustion chamber CC3, the Soviets appear to have a plasma generator which is reliable and can be counted on for long duration operation. The gas generator specifications as originally provided by the Soviets, along with the modifications of 22 October 1974, are given below in Table 2.2-1.

TABLE 2.2-1

U-25 GAS GENERATOR AND EXHAUST SYSTEM SPECIFICATIONS

	<u>U-25 Ref. Data</u> ⁽³⁾	<u>October 1974</u>
Oxidant flow rate	45 kg/sec	49 kg/sec
Oxygen enrichment	40% by weight	42% by weight
Fuel	natural gas (per spec)	natural gas
Fuel flow	5.3 kg/sec	5.8 kg/sec
Preheat temperature	1200 - 1250°C	1200 - 1250°C
Heat losses	4%	4%
Combustion pressure	3.2 abs atm	3.2 abs atm
Steam generator inlet pitot pressure	1 ± .02 atm	1 ± .02 abs atm
Steam generator inlet temperature at 50 kg/sec	2400°C	Continuous operation without MHD load under above max. conditions.
Seed	K ₂ CO ₃ wet or dry	same
Starting time	20 minutes	same

2.2.2 U-25 Exhaust System. The U.S. diffuser will discharge into a steam generator which is apparently of novel construction. In the specifications originally provided by the Soviet side in July 1973, the heat absorption capability of the steam generator was inadequate to accept the full heat load provided by 50 kg/sec flow at maximum enrichment without load on the MHD generator. Thus for all intents and purposes the flow capability of the U-25 would need to be de-rated to take this into account. When this was done, the maximum flow would need to be reduced to something of the order of 43 to 44 kg/sec. The initial MEPPSCO designs were geared to this flow rate. With the 22 October 1974 modifications to the specifications, the steam generator will accept a flow of 54.8 kg/sec at maximum enrichment without load on the MHD generator. Thus, the maximum capability of the steam generator and that of the gas generator are now compatible without load on the MHD generator. For all intents and purposes, the heat absorption capability of the steam generator is no longer a problem for the design of the U.S. channel.

2.2.3 U-25 Gap Dimensions and Field Distribution. Figure 2-1 shows the pertinent U-25 gap dimensions and the field distribution with a maximum field of 2 Tesla. Also shown on the figure is the approximation to the field distribution which is utilized in the MEPPSCO calculations. The modification consists essentially of two straight lines in the fringe field and a constant field in the main portion of the gap. It is felt that there is little point in being more exact about the field distribution in the fringe regions since the calculations do not consider the magnetic field conservation equations in any case. It should be noted that the Soviets are committed to increasing the maximum field distribution to 2.2 Tesla by increasing the current flow in the windings of the magnet and the field of 2.2 Tesla has been used for the majority of the MEPPSCO design calculations. It should also be noted that at the 22 October 1974 meeting, the Soviets suggested that shims might be utilized with the American channel to increase the magnetic field at the upstream end of the channel where the MEPPSCO design has a good bit of clearance between the poles of the magnet. This has not been taken into account in the design.

2.2.4 Coolant Supply Specifications. The specifications of the cooling system for the U.S. equipment including all of the equipment as provided by the Soviet side are given in the table below.

Two sets of specifications are given. The first are the numbers originally provided by the Soviet side in July 1973, while the second reflects the modifications agreed to by the Soviets on 22 October 1974. As with the gas generator, the MHD cooling equipment specifications for the U-25 are without parallel in the world today.

Fig. 2-1.

U-25 GAP & FIELD DISTRIBUTION!

TABLE 2.2-2
U-25 COOLANT SPECIFICATIONS

	<u>Original Specs.</u>	<u>October 1974</u>
Cooling medium	Water	Water
Flow (maximum)	560 metric tons/hr	680 metric tons/hr
Inlet pressure (maximum)	50 abs atm	40 abs atm
Inlet temperature (maximum)	40°C	40°C
Outlet temperature (maximum)	100°C	100°C
Outlet pressure (minimum)	6 abs atm	6 abs atm

2.2.5 Power Conditioning Specifications. The Soviet power conditioning equipment consists of 48 separate inverters which can condition the output of the MHD generator directly for application to the Moscow power grid. These inverters are specifically intended for use with segments of electrode type MHD generators with multiple outputs and it is understood that the Soviets plan to increase the capability to 96 inverters by the time the U. S. channel is delivered.

The U-25 power conditioning equipment must also be considered unique in the entire world. On the other hand, it illustrates the difficulty of designing an MHD generator for the kind of multiple outputs that would realistically be required for a segmented electrode Faraday generator or even for a diagonal generator with current tapping and bleeding and so on. It has always appeared to us that it is impossible to go from a single output to a few outputs and indeed if you try to do so the result is generally a catastrophic arcing in the MHD generator. Experience would indicate that for a base load MHD generator with separately loaded segmented electrode pairs that something of the order of 2,000 output circuits would be required, all more or less of the same voltage-current rating. For a diagonal generator with current bleeding and tapping, the number of output circuits is something of the order of the number of electrodes which are subtended by the diagonals at the channel ends. Although this number is substantially less than that of a segmented electrode Faraday design, several hundred circuits are still required for a large installation, and in the case of the diagonal the ratings of these circuits would vary widely. It is primarily the consideration of the power conditioning problem which led MEPPSCO to select the design intended for a single output.

The power conditioning specifications are substantially relaxed with a single output. The capability of the Soviet inverters in a single output is several times that required to absorb the output of the MEPPSCO channel. The only constraint on the design becomes the maximum voltage withstand capability of the combustion chamber to ground which at the present time is 5000 Volts according to the Soviet specifications.

2.2.6 Nozzle and Diffuser Interface Specifications. The U.S. nozzle must mate to the Soviet combustion chamber exit nozzle while the diffuser must mate up to the inlet of the steam generator.

The mating of the combustion chamber exit to the U.S. nozzle appears to be straightforward and does not influence the design appreciably. The diffuser interface exerts more of an influence on the design primarily because of the relatively short distance that has been provided for the diffuser. With the close coupling to the steam generator, it becomes necessary to begin diffusion while actually substantially inside the magnetic field in order to limit the diffuser wall angles to acceptable levels.

2.2.7 Mechanical Constraints on the Form of the Wall Angle Variation. In a variable angle windowframe diagonal generator, the variation in wall angle is implemented by tapering the individual windowframes. (A flat gasket or O-ring and spacer is sandwiched between the frames.) The rate of wall angle variation is constrained by the amount of taper that can be accommodated in a single plate when the breakdown voltage of the channel and the necessity to include a water cooling passage in the frame are considered. This is illustrated in Fig. 2-2.

We have that

$$\Delta\theta = \frac{\delta}{d_2 \sqrt{1+\phi^2}} \quad (1)$$

where $\Delta\theta$ is the change in θ in a single frame, d_2 is the channel dimension in the $\bar{U} \times \bar{B}$ direction, $\phi = E_y/E_x = \tan \theta$ and $\delta = t_2 - t_1$ is the difference in frame thickness at the two ends. But $\Delta\theta$ occurs in a displacement along the channel axis, $\Delta x = \bar{t} \sqrt{1+\phi^2}$ where $\bar{t}$ is the centerline thickness of frame plus insulator, $\bar{t} = (t_2 + t_1)/2$. Therefore, assuming that $\Delta\theta$, and Δx can be replaced by $d\theta$ and dx , we have:

$$\frac{d\theta}{dx} = \frac{\delta}{d_2 \bar{t} (1+\phi^2)} = \frac{\delta}{d_2 \bar{t} \sec^2 \theta} \quad (2)$$

or

$$\tan \theta - \tan \theta_0 = \phi - \phi_0 = \frac{\delta}{d_2 \bar{t}} (x - x_0) \quad (3)$$

Fig. 2-2. WALL ANGLE VARIATION CONSTRAINTS

which determines the form of the wall angle variation. θ_0 and x_0 are the initial conditions.

Considering a $3/16''$ water passage with $1/32''$ minimum walls, a $1/16''$ insulator, and a maximum pitch of $1/2''$ gives:

$$\begin{aligned} t_1 &= 5/16'' \\ t_2 &= 1/2'' \\ \delta &= 3/16'' \\ \bar{t} &= 13/32'' \\ \delta / \bar{t} &= 0.462 \end{aligned}$$

2.2.8 Dual Compatibility with AEDC HPDE Magnet. The design requirement has been imposed that the U-25 channel will also be compatible with the High Performance Demonstration Experiment magnet at AEDC. Such a requirement is a distinct advantage in that it will permit the U-25 channel, or an identical version, to be examined in the AEDC High Performance Facility where the magnetic field strength can be as high as 4 Tesla in a continuous operation.

The U-25 magnet is a minimum ampere turn design with a pancake gap very short in the B direction. On the other hand, the AEDC magnet is a high field strength design with the design such that the field coils are close in and the gap is more or less square. Thus, the problem with compatibility becomes one of limiting the width of the channel in the $U \times B$ direction at AEDC, and in the B direction at the U-25. A sketch of the gap dimensions and magnetic field at AEDC is shown in Fig. 2-3 along with the approximation utilized by MEPPSCO for the purpose of design calculations.

Although it is clear that the performance of the channel will be much improved at higher field strength in the AEDC facility, the performance has not been examined in detail here. Rather, we have limited ourselves to assuring mechanical compatibility. That compatibility is discussed in more detail in Section 2.4. We should only mention here that the small wall thickness of the windowframe design assures that the dual compatibility is not much of a problem for the MEPPSCO design.

2.3 Electrical Schematic and General Description of the Design Performance Analysis

Figure 2-4 (Drawing No. U-25-1312) shows the U-25 electrical schematic and illustrates the manner in which the design flow analysis is broken down into the various regions comprising the entire channel. The U-25 flux distribution is also indicated.

Fig. 2-3.

AEDC GAP & FIELD DISTRIBUTION

Fig. 2-4. U-25 Electrical Schematic

For the purposes of the calculation, the channel is broken down into five regions as follows:

Region 1	Inlet power takeoff
Region 2	Upstream transition
Region 3	Channel proper
Region 4	Downstream transition
Region 5	Outlet power takeoff

The total length of the windowframe along the axis of the channel is 6.80 meters comprising the distance from the flange between the nozzle and Region 1, to the flange between the diffuser and the exit of Region 5. The total channel length to the upstream end of the first frame is 6.95 meters. The delineation of the regions is as follows:

Region 1 is the inlet power takeoff. Although this region is composed entirely of windowframes which are insulated from each other as in the basic channel construction, electrically these frames are all connected together and to the nozzle. It is in this region that the output current is transferred to the generator walls. Because all of the frames are connected together, both E_x and E_y are zero in this region. Therefore, the flow analysis considers this region to be a short circuited, single electrode, Faraday generator in which the transverse current J_y is given by:

$$J_y = \frac{\sigma UB}{1 + \Omega^2} \quad (4)$$

where σ is the gas conductivity, U the gas velocity, B the field strength, and Ω the local Hall coefficient. For the purpose of the design analysis, the velocity is held constant in this region. In Region 1, as well as in Region 2, the wall angle is being increased at the maximum rate which was discussed under Section 2.2.7 above.

Region 2 is a transition section between the power takeoff section and the channel proper. In Region 2, the wall angle is still being increased at the maximum possible rate but the diagonalization condition which will be developed in the following section will not be applied in this region. The interface between Region 1 and Region 2 is intended to be the axial station where the electric field goes to zero, that is the field according to the one dimensional analysis. When this point is found, it will represent the maximum output that the channel will deliver and as well minimize the danger of destructive arcing. The principle was conclusively demonstrated during the modifications to the LORHO Pilot Generator when movement of the power takeoff to the region where the field was zero

completely eliminated all such arcing.

Of course, the prediction of the point of zero field by the one dimensional analysis is not accurate and indeed it may be stated that we would not be confident that any analysis would accurately predict this point. Thus a crucial feature of the MEPPSCO design is the ability to change the point of power takeoff. This is illustrated in Fig. 2-4 by the switches indicated on either side of the supposed Region 1/Region 2 interface. These switches can be operated from the control room. It is supposed that the most upstream of these switches will be well upstream of the point where the field reverses. In actual operation, the channel is started up with all of the switches open. The field will then reverse in the upstream part of the generator. The procedure would then be to close the switches successively moving downstream until the point of field reversal had been achieved. With this procedure, it is necessary that the switches only be rated for closure and not to open the circuit. In the design analysis, Region 2 is considered as a constant current diagonal without the diagonalization conditions being applied. In our design analysis, Region 2 is considered as a region of constant velocity.

Region 3 may be considered as the channel proper and is the region where most of the power produced by the channel is generated, that is a region of accelerating flow at the design condition. It is also a region where the diagonalization conditions are satisfied and where the channel dimensions are chosen such that these conditions are satisfied.

Regions 4 and 5 are the downstream equivalents of upstream Regions 1 and 2, and again switches are provided to vary the position of the power takeoff. One difference between Region 5 and Region 1 is that diffusion begins in Region 5 because of the relatively limited space provided for the diffuser before the steam generator interface.

The effective stagnation pressures at the junctions of the various regions in the upstream section are indicated on Fig. 2-4. It is seen that a pressure drop of approximately 0.24 atmospheres occurs in the inlet power takeoff section, while a pressure drop of approximately 0.09 atmospheres occurs in the exit power takeoff section. These pressure drops are particularly annoying in a channel of low pressure ratio like the U-25.

In the design analysis, the five regions delineated above are analyzed separately and the solutions are in effect patched together at the boundaries between the various regions.

The actual layout of the channel and selection of the critical frame angles is somewhat arbitrary and involves something of a feel for what is possible. We have arbitrarily selected a maximum wall angle tangent of 1.2, and this value occurs 1.4 meters downstream of the channel inlet flange. With this selection of maximum wall angle and station, the constraints on wall angle variation

developed under Paragraph 2.2.7 above specify the wall angle at the nozzle-channel and diffuser-channel interfaces. If the upstream end of the first frame begins at the end of the nozzle as shown, we can write that

$$\phi - \phi_0 = \frac{\delta}{d_2 t} (x - x_0) \quad (5)$$

The maximum value of ϕ in the upstream end of the channel has been set somewhat arbitrarily at 1.2, and we desire to achieve this value of ϕ approximately one (1) diameter into the region of uniform field so that the frame at $\phi = 1.2$ is well within the uniform field. Thus, $\phi = 1.2$ at $x = 1.4$ meters downstream of the upstream end of the nozzle-channel flange. The value of d_2 remains constant at 0.73 meters in Regions 1 and 2. Thus we have for the inlet:

$$\phi - \phi_0 = 0.633 (x - x_0) \quad (6)$$

It is desirable to orient the frame at $x - x_0$, normal to the flow direction, however, for this to be the case $\phi = 1.2$ could not be reached until $x = 1.89$ meters. Thus, we must compromise and angle the nozzle-channel flange from the normal to the flow. If the axial station x is measured from the upstream end of the first channel flange, and we constrain $\phi = 1.2$ at $x = 1.4$, then:

$$x_0 = 1/2 \phi_0 d_2 \quad (7)$$

where ϕ_0 and x_0 are to be found. Substituting into Eq. (3) gives:

$$\phi_0 = \frac{1}{\left(1 - \frac{\delta}{2 t}\right)} \left(\phi - \frac{\delta x}{d_2 t}\right) \quad (8)$$

which gives $\phi_0 = 0.408$, $x_0 = 0.149$ cm, and $\theta_0 = 22^\circ 12'$.

As shown in Fig. 2-4, the one dimensional analysis indicates that the Region 1 - Region 2 interface will be near $x = 0.55$ meters, where $\phi = 0.66$. Thus, the first frame, even though angled to the normal, is well separated from the point of power takeoff.

In Region 3, the wall angle is decreased linearly with $(d\phi / dx) = 0.155/m$ to axial station 5.9 meters where $\phi = 0.5$. From there, ϕ is decreased at the maximum rate for 1.05 meters to normal with the axis at the channel-diffuser flange at $x = 6.95$ m. The indicated position of the power takeoff is at $x = 6.25$ m where $\phi = 0.344$. There is ample room between the point of power takeoff and the diffuser.

2.4 Design Flow Analysis of a Single Output Diagonal MHD Channel

In a single output diagonal generator, the current, I , is a constant of the motion. In the one dimensional approximation, I is given by:

$$I = (j_x + \phi j_y) A_c \quad (9)$$

where j_x and j_y are the transverse and longitudinal current densities, ϕ is the ratio of E_y/E_x and A_c is the inviscid flow area. It should be emphasized that this is a one dimensional approximation but it is a good approximation in the case of conducting side walls where the axial current density is not too high. It is easy for detailed current continuity conditions to be satisfied with the conducting side walls since the current can flow easily to the gas from the side walls along the magnetic field lines.

For the design flow analysis, the other factors specified in addition to the current are the velocity gradient together with the inlet conditions. For the design analysis, the inlet conditions and velocity gradient are selected with the inlet of achieving a choked exit in a subsonic accelerating flow. With the velocity gradient specified, the program computes the channel area distribution as a function of distance. It is necessary to select the current and conductivity so that the exit conditions permit recovery to ambient pressure with a subsonic diffuser. A slight amount of juggling is usually necessary in order to achieve this.

The U-25 channel must be compatible both with the AEDC and U-25 magnets. Due to the magnetic field levels for which these magnets are designed they are of radically different geometry. The U-25 magnet is a minimum ampere turn, two (2) Tesla design with a pancake shaped aperture relatively short along the field lines and with large extent in the $U \times B$ direction. The AEDC magnet, on the other hand, is a high field strength design with a more or less square aperture. The relatively thin walls of the windowframe channel permit the channel to be designed with compatibility for both magnets.

There is, however, a further condition on compatibility which must be satisfied for a single output diagonal. We have seen that detailed current continuity can be achieved by conduction to the side walls. However, there are further conditions on the electric field which must be satisfied since the conducting diagonals impose conditions on the electric field strength along their length and at the ends where they intersect the electrode walls, that is, the voltage difference between adjacent frames is a constant along a frame. Thus, in reality, even with a one dimensional flow, the solution of the electric field for a window-frame diagonal is a complex electric field boundary value problem. An important part of the MEPPSCO one dimensional analysis is the attempt to preserve the one dimensional, initial value characteristic of the analysis. This is done by developing an approximate criterion for the electric field to satisfy at a local

point but which expresses the field conditions at other points along the channel. This condition will be developed in the next section and may be stated as:

$$V_T = \text{constant}$$

where V_T is the transverse voltage developed across the channel. While the one dimensional analysis is used to generate the channel area distribution, the condition on V_T is used to determine the aspect ratio of the channel. The condition on V_T appears to be a sufficient condition for the electric field in the one dimensional approximation. We do not at this time know how necessary it is. Calculations carried out by ARO, Inc. in connection with the HPDE Channel LP-2 have indicated that the condition on V_T need not be too closely adhered to. It would be of interest to determine the influence of departure from this condition in more detail.

2.4.1 Diagonalization of a Single Output DCW MHD Generator. In the design of a single output diagonal MHD channel, it is usual to assume that the total current, I , where:

$$I = A (j_x + \phi j_y) \quad (10)$$

is a constant, where:

$$\phi = E_y / E_x \quad (11)$$

A is the channel area and j_x and j_y are the axial and transverse current densities, respectively. (In a real generator, ϕ and E_x are both negative; they are treated as positive here for convenience.) This is a statement for every axial station on the channel, and assumes that all quantities are uniform over the channel, and assumes that all quantities are uniform over the channel area at each station. Certainly, in any practical situation this is never strictly true, but ideally this is a necessary condition. However, it is not a sufficient condition for a proper full ideal diagonalization, since detailed conditions on the potential distribution must also be satisfied. Our purpose here is to develop these conditions in such a way as to permit their inclusion in a one dimensional analysis. Initially, electrode drop will be neglected.

Figure 2-5 illustrates a portion of a diagonalized MHD channel where it has been assumed that the equipotentials are straight lines, with inverse slope ϕ defined at the station x_0 where the equipotential cuts the channel centerline. A second equipotential cuts the channel centerline a distance, Δx downstream at $x_0 + \Delta x$, at a different value of ϕ :

$$\phi(x_0 + \Delta x) = \phi(x_0) + \left. \frac{d\phi}{dx} \right|_{x_0} \Delta x = \phi(x_0) + \phi'(x_0) \Delta x$$

Fig. 2-5. WINDOW FRAME MECHANICAL ELECTRICAL COMPATIBILITY

where Δx can be considered an infinitesimal distance. Since these two straight lines are equipotentials, the voltage difference between them must be the same along their entire length, and in particular at their ends. The voltage difference, ΔV , between the axial stations on the electrode wall separated by a (axial) distance Δ is given by:

$$\Delta V = \sqrt{\left(E_x + \frac{h}{2} \frac{dE_y}{dx}\right)^2 + \left(\frac{E_x}{2} \frac{dh}{dx}\right)^2} \quad (12)$$

where h is the distance between electrode walls. Now, the equipotential cutting the axis at x_0 intersects the positive and negative electrode walls at x^+ and x^- , respectively. The respective separation between the two equipotentials separated by Δx at x_0 on the axis are separated by Δx^+ and Δx^- at the electrode walls. Clearly there is a definite geometric relationship among Δx^+ , Δx^- , ϕ , and h totally independent of the generator flow and electrical analysis, but imposing a constraint on that analysis. The constraint is the statement that ΔV is the same at both ends of the equipotentials, intersecting the axis at x_0 with an infinitesimal separation Δx :

$$\Delta x^+ \sqrt{\left(E_x + \frac{h}{2} \frac{dE_y}{dx}\right)^2 + \left(\frac{E_x}{2} \frac{dh}{dx}\right)^2} \Big|_{x^+} = \Delta x^- \sqrt{\left(E_x + \frac{h}{2} \frac{dE_y}{dx}\right)^2 + \left(\frac{E_x}{2} \frac{dh}{dx}\right)^2} \Big|_{\Delta x^-} \quad (13)$$

Again, Δx^+ and Δx^- are infinitesimal quantities. Since $(x^- - x_0)$ and $(x_0 - x^+)$ are not small quantities, a boundary value problem of considerable complexity would need to be solved in order to obtain a one dimensional solution for the generator analysis if the above constraint is to be satisfied exactly. Such a complication seems unwarranted at the present time and we desire to develop an approximate way to express this constraint at x_0 so that the initial value character of the basic one dimensional flow solution may be preserved. To do this, Δx^+ , Δx^- , ΔV^+ and ΔV^- must be expressed in terms of quantities at x_0 . The results are approximate since only first order terms will be carried.

To first order, x^+ and x^- are given by (remember it has been assumed that the equipotentials are straight lines):

$$\begin{aligned} x^- &\approx x_0 + \frac{\phi h}{2} \left(1 + \frac{\phi h'}{2} \right) \\ x^+ &\approx x_0 - \frac{\phi h}{2} \left(1 - \frac{\phi h'}{2} \right) \end{aligned} \quad (14)$$

where now all quantities on the right are the values at x_0 . The values of Δx^- and Δx^+ can be found to first order by differentiating the above expression with respect to x at x_0 and putting, for example:

$$\Delta x^- = \left. \frac{dx^-}{dx} \right|_{x_0} \Delta x \quad (15)$$

The result is

$$\frac{\Delta x^-}{\Delta x^+} = \frac{1 + \frac{\phi h'}{2} + \frac{h\phi'}{2}}{1 - \frac{\phi h'}{2} - \frac{h\phi'}{2}} \quad (16)$$

to first order. Usually in a generator, ϕ' is negative (with ϕ positive) and h' is positive. Since the minimum value of Δx^- is zero, (corresponding to $E_x \rightarrow \sigma$), it is clear that to first order:

$$(1 + \phi h' + h\phi') > 0 \quad (17)$$

in order that the equipotentials do not cross. Thus, the rate of change of ϕ is limited from purely geometric considerations.

Now, it is necessary to compute ΔV at x^+ and x^- . In Eq. (12) with $E_y = \phi E_x$ we have:

$$\Delta V = \phi E_x \sqrt{1 + \left(\frac{\phi h}{2}\right)^2 \left(\frac{h'}{h} + \frac{\phi'}{\phi} + \frac{E_x'}{E_x}\right)^2} \quad (18)$$

But

$$\phi E_x h = E_y h = V_t \quad (19)$$

where V_t is the local transverse voltage across the channel, electrode drop not included. Thus,

$$\frac{h'}{h} + \frac{\phi'}{\phi} + \frac{E_x'}{E_x} = \frac{V_t'}{V_t} \quad (20)$$

So that

$$\Delta V = \mathcal{A} E_x \sqrt{1 + \left(\frac{\phi h}{2}\right)^2 \left(\frac{V_t'}{V_t}\right)^2} \quad (21)$$

If, in Eq. (21) we put $x = \eta L$ where η is a nondimensional length and L is the channel geometric length

$$\Delta V = \mathcal{A} E_x \sqrt{1 + \left[\frac{\phi}{2(L/h)}\right]^2 \left(\frac{V_t'}{V_t}\right)^2} \quad (22)$$

where now the differentiation is with respect to η instead of x . Since (V_t'/V_t) can at most be of the order unity in an effective diagonalization, (it will turn out to be zero), the order of magnitude of the various quantities is:

$$\frac{V_t'}{V_t} = 0 \quad (1')$$

$$\phi = 0 \quad (1)$$

$$L/h = L/D = 0 \quad (5-10)$$

$$\left[\frac{\phi}{2(L/h)}\right]^2 \left(\frac{V_t'}{V_t}\right)^2 < 0 \quad (10^{-2})$$

so that to good accuracy:

$$\Delta V = \mathcal{A} E_x \quad (23)$$

So that Eq. (13) becomes, using Eq. (16):

$$\frac{1 + \frac{\phi h'}{2} + \frac{h \phi'}{2}}{1 - \frac{\phi h'}{2} - \frac{h \phi'}{2}} = \frac{E_x^+}{E_x^-} \quad (24)$$

But

$$E_x \cong E_x(x_0) + \frac{dE_x}{dx} (x - x_0)$$

to first order so that Eq. (24) becomes, to first order, using Eq. (14)

$$\frac{\phi'}{\phi} + \frac{h'}{h} + \frac{E_x'}{E_x} = \frac{V_t'}{V_t} = 0$$

Thus, to first order, the condition for an effective diagonalization is that V_t , the transverse voltage across the channel, should be a constant. Although this condition was developed without considering electrode drop, it will apply equally well with electrode drop if the electric fields are taken as the externally observable values. The condition that $V_t = \text{constant}$ leads naturally to a design in which the distance between electrode walls is increased at the front of the channel to a value that does not unduly compromise the magnet design. Since channel area and generally the axial electric field increase as the gas progresses down the channel, while ϕ decreases, the condition is a compatible one which tends to bring the channel near square towards the exit as is most desirable.

It seems most reasonable to apply the above conditions only in those parts of the channel where ϕ is varying slowly and where the magnetic field is uniform. Thus, in the design flow analysis, the condition $V_t = \text{constant}$ is applied only in Region 3, the central part of the generator.

2.5 Description of the Flow Analysis

An available computer program called BEDAG is utilized for the design flow analysis. The calculations performed by BEDAG are described here:

2.5.1 Thermodynamic Properties. The thermodynamic properties of the working fluid are stored in tabular form and an interpolation routine is used to determine the properties at any channel station. The following variables are stored:

P	pressure
h	enthalpy
T	temperature
ρ	density
(γR)	ratio of specific heats, times gas constant
σ	electrical conductivity
μ	electron mobility

For the U-25 design, the data is stored for pressures of 0.6-3.2 atm in steps of 0.1 atm, and temperatures of 2400°K to 3000°K in 50°K increments. In the interpolation, p and h are used as the independent variables and the routine

returns the other five properties. In addition, the derivatives $\frac{\partial \rho}{\partial p}|_h$ and $\frac{\partial \rho}{\partial h}|_p$ are computed. The sound speed, $\sqrt{a^2}$ is given by:

$$\frac{1}{a^2} = \frac{\partial \rho}{\partial p}|_h + \frac{1}{\rho} \frac{\partial \rho}{\partial h}|_p$$

and the gas constant, R, by

$$R = \frac{P}{\rho T}$$

2.5.2 Initial Conditions. The initial conditions which are specified are:

pressure	inlet length for boundary layer boundary layer voltage drop parameters
enthalpy	fluid viscosity effective wall roughness height
mass flow	enthalpy ratio for electrode wall wall friction law
channel inlet dimensions	initial value of momentum thickness
zero station relative to field integration interval	initial power and voltage
field distribution	initial value of shape factor
channel length	diffuser efficiency
conductivity constant	limiting minimum pressure recovery
Ω/B constant	current
velocity distribution	wall angle distribution

From these conditions, inlet velocity and all other properties are determined.

2.5.3 Calculations. With the current, I, specified and the electrode drop, V_e , assumed as:

$$V_e = V_i + C j_y x \quad (25)$$

i. e., the sum of a constant potential and a linear resistor roughly proportional to the boundary layer thickness. With p and h specified, inlet density and other thermodynamic properties are determined by reference to the stored thermodynamic data. As the initial boundary layer thickness is known, the inviscid core area, A_c , is determined from:

$$A_c = (d_1 - 2\delta^*) (d_2 - 2\delta^*) \quad (26)$$

where d_1 and d_2 are the inlet B and E dimensions respectively, and δ^* is the boundary layer displacement thickness. The inlet velocity, U , is then found from:

$$u = \dot{m} / \rho A_c \quad (27)$$

and all the inlet conditions can now be determined.

It is most convenient first to calculate the internal axial electric field, E_x , from:

$$E_x = \left[\frac{I (1 + \Omega^2)}{\sigma A_c} + uB (\phi - \Omega) \right] / (1 + \phi^2) \quad (28)$$

where the wall angle tangent, $\phi = E_y / E_x < 0$ is specified as a function of axial station. It should be noted that there are other ways of obtaining a design loft than specifying ϕ and calculating the channel area. For instance, A could be specified and ϕ calculated. However, mechanical considerations dictate that ϕ must be closely controlled in order to achieve a design that can be fabricated. It is for this reason that the present formulation of the design problem was selected. We have further that:

$$\begin{aligned} j_y &= \sigma [(\phi + \Omega) E_x - uB] / (1 + \Omega^2) & a) \\ E_y &= \phi E_x & b) \\ j_x &= \frac{I}{A} - \phi j_y & c) \\ V_t &= d_{2c} E_y - V_e & d) \end{aligned} \quad (29)$$

The value of V_t as computed at the inlet of Region 3 is taken as a constant throughout Region 3 and is used to determine the channel output ratio. Obviously, this procedure limits this detail of the analysis to regions where the magnetic field is relatively uniform so that the ends of the generator in the fringe field cannot be so analyzed. In Regions 2 and 4, one of the dimensions is selected for convenience and the other is computed. In any case, the one dimensional analysis is not of real use in the fringe regions of a diagonal generator since at least the potential and field distribution are far from one dimensional in the fringe field where the power takeoff occurs.

With the electrical quantities determined, we are now in a position to compute dA_c/dx :

$$\begin{aligned} \frac{dA_c}{dx} = & - \frac{A_c}{1+\phi^2} \left\{ \left. \frac{\partial \rho}{\partial h} \right|_p \left[- (1 + \phi^2) u \frac{du}{dx} + \frac{I u B (\phi - \Omega)}{\rho \dot{m}} \right] \right. \\ & - \left. \left. \frac{\partial \rho}{\partial p} \right|_h \left[u (1 + \phi^2) \frac{du}{dx} + \frac{\sigma u B^2}{\rho} \right] + (1 + \phi^2) \frac{1}{u} \frac{du}{dx} \right\} \quad (30) \\ & - \frac{1}{1 + \phi^2} \left[\left. \frac{\partial \rho}{\partial p} \right|_h \frac{I B}{\rho} (\phi + \Omega) + \left. \frac{\partial \rho}{\partial h} \right|_p \frac{I^2 (1 + \Omega^2)}{\sigma \rho \dot{m}} \right] \end{aligned}$$

which utilizes the fact that:

$$d\rho = \left. \frac{\partial \rho}{\partial p} \right|_h dp + \left. \frac{\partial \rho}{\partial h} \right|_p dh \quad (31)$$

together with the energy, momentum and continuity equations.

With j_y and hence V_e , as well as the new core area determined, d_{2C} , the E dimension is given by:

$$d_{2C} = (V_t + V_e) / \phi E_x \quad a)$$

while:

$$d_2 = d_{2C} + 2\delta^* \quad b)$$

$$d_{1C} = A_c / d_{2C} \quad c) \quad (32)$$

$$d_1 = d_{1C} + 2\delta^* \quad d)$$

$$A = d_1 \times d_2 \quad e)$$

The electric field E_x computed above is the internal field. The observed axial electric field E_{xx} is less than E_x by an amount dependent on the electrode voltage drop. The power output is obtained by integrating

$$\frac{dP_{out}}{dx} = I E_{xx} \quad (33)$$

where E_{xx} is computed from:

$$E_{xx} = \frac{(\phi d_2 C E_x - V_e)}{\phi d_2} \quad (34)$$

The boundary layer is computed using a modified momentum integral method which accounts for the $\bar{j} \times \bar{B}$ forces together with the Garner correlation equation for the shape factor. ⁽⁴⁾ The equation for the momentum thickness is:

$$\frac{d\Theta}{dx} = \frac{C_f}{2} - \Theta \left[\frac{1}{U} \frac{dU}{dx} (H_i + 2) + \frac{1}{\rho} \frac{d\rho}{dx} \right] \quad (35)$$

where Eq. (31) is used to find $d\rho$. In the above:

$$\begin{aligned} \Theta &= \text{momentum thickness} \\ C_f &= \text{friction coefficient} \\ H_i &= \text{incompressible shape factor} \end{aligned}$$

The shape factor correlation equation of Garner is:

$$\frac{dH_i}{dx} = \left[-\frac{1}{U} \frac{dU}{dx} - \frac{.0135 (H_i - 1.4)}{\Theta} \left[\frac{U \cdot \Theta}{EMU} \right]^{.1666667} \right] \text{EXP}[5 (H_i - 1.4)] \quad (36)$$

The actual boundary layer displacement thickness, δ^* is given by: $\delta^* = H_c \Theta$ where H_c is the compressible shape factor which is different from H_i . An approximate value for δ^* can be obtained from the definitions for δ^* and Θ by assuming a perfect gas with constant specific heats for a specific wall enthalpy ratio, and by utilizing the Prandtl relation between the velocity and temperature fields. The resultant integrals cannot be evaluated in closed form and must be evaluated numerically at each step. This is time consuming. A different procedure is used in BEDAG. We can write that:

$$H_c = (H_i, M, \gamma, h_w/h)$$

where the relation cannot be given in closed form. However, for fixed γ and h_w/h , the values of H_c were computed as a function of H_i and M_i and the results approximated by a curve fit over the Mach number range of interest. A subroutine interpolates the curve fits for each station. The computer time required to do this is trivial compared to that required for the integration.

In the actual computation, a four point Runge-Kutta routine is used to solve the differential equations. The differentials are dU , dP , dh , dH_i , $d\theta$, dV and dP_{out} . A large number of additional quantities are computed and 42 of them appear on the "big printout." These include all the local quantities, as well as hot and cold wall heat transfer rates for electrode and slant walls and local diffuser recovery pressure for specified diffuser efficiency.

Typical UNIVAC I108 time share execution time for program BEDAG with the U-25 channel at 0.1 meter intervals is two (2) seconds; run cost is approximately one dollar.

2.6 Results and Gas Side Loft

During the course of the preliminary design, several hundred runs were carried out to arrive at the gas side loft. Several interim lofts were developed at various stages in the design process both to get the mechanical design off the ground and to provide material for interaction with STD Research, Inc. (STD). STD carried out off-design analysis including end effects and electrode drop effects as well as studying the influence of a slag layer. Revision 1, Revision 2 and Revision 3 were essentially concerned only with Region 3 of the generator, that is the channel proper itself, and did not consider the transition or power takeoff regions for computing the power output and total pressure losses. Revision 4 was the first to consider all five regions of the generator and the design was carried out for a mass flow of 44 kg/sec. Revision 5 is essentially the same as Revision 4 with the mass flow increased to 50 kg/sec as per the change in U-25 specifications at the 22 October 1974 meeting with the Soviet side. Revision 6, the final loft, reflects the most realistic integration of the mechanical constraints regarding the change in wall angle at inlet and outlet of the generator and the integration of the generator design with the nozzle design. Specifications for typical operating conditions for Revision 6 are given on the following pages.

The Revision 6 gas side loft of the channel is shown in Fig. 1-2 (Drawing No. U-25-1290-1). Figures 2-6 through 2-11 present the variation of some of the important quantities throughout the channel and in Table 2.6-3 a typical operational summary is shown. In Appendix 2 the channel loft, wall angle and magnetic field are given as a function of axial station in tabular form. Certain computer printouts of the design case are also presented in Appendix 2.

Fig. 2-6. Channel Dimensions in Meters vs Axial Position for U-25 (Rev. 6) Channel

Fig. 2-7. Velocity, Static Pressure and Recovery Pressure vs Axial Position for U-25 (Rev. 6) Channel

Fig. 2-8. Magnetic Field and Wall Angle vs Axial Distance for U-25 (Rev. 6) Channel

Fig. 2-9. Voltage, E_{xx} and $\bar{E}$ vs Axial Distance for U-25 (Rev. 6) Channel

Fig. 2-10. Momentum and Displacement Thicknesses vs Axial Distance for U-25 (Rev. 6) Channel

Fig. 2-11. Compressible and Incompressible Shape Factors vs Axial Distance for U-25 (Rev. 6) Channel

TABLE 2.6-3

U-25 SOD CHANNEL, REVISION 6
TYPICAL OPERATIONAL SUMMARY I = 2784 AMPS

Mass flow:	50.0 kg/sec
Working fluid:	stoichiometric products natural gas and $N_2/O_2=1.72$ by volume preheated to $1200^{\circ}C$ (actual composition per Soviet U-25 Ref. Data, p.2)
Seed:	K_2CO_3 hot aqueous solution
Stagnation enthalpy:	158 cal/gm referred to elemental reactants (C, H_2 , O_2 , N_2) at $0^{\circ}K$
Combustion pressure:	3.20 atm
Inlet stagnation pressure loss (estimated) Region 1:	0.24 atm
Effective inlet stagnation, pressure ($x=0.55$, $\theta = 22^{\circ}15'$):	2.96 atm
Channel inlet flange:	STA(-27.8) (STA 0 at break in pole edge)
Zero for calculation:	STA(-6.2), ($\bar{E} = 0$)
Friction law assumed (fully rough wall)	$C_f = \left\{ 2.87 + 0.685 \log_{10} \left(\frac{x + l_o}{K_{s_{eff}}} \right) \right\}^{-2.5}$ $l_o = 1 \text{ m}$ $K_{s_{eff}} = .0025 \text{ m}$
Cross section at $x=0$:	0.331m(B) x 0.730m(E), $A = 0.242m$
LOA	6.95m (5.70 active)
Inlet wall angle:	$22^{\circ}15'$

TYPICAL INLET CONDITIONS

Velocity:	914 m/sec (M=0.89)
Pressure:	1.91 atm
Enthalpy (0°K)	$2.47 \times 10^5 \text{ J/kg}$
Temperature:	2787°K
θ :	.002M (assumed)
$\bar{H}$:	1.28 (turbulent flat plate-zero gradient)
$\bar{H}_c$: (compressible)	0.708
δ_c^* :	.0014M
C_f :	.0078
σ :	7.3 Mho/m
Ω :	0.55
B :	2.2 T
Active length:	5.70M

TYPICAL CONDITIONS EXIT OF ACTIVE SECTION

Static pressure:	0.726 atm
Velocity:	993 m/sec (M=1.0)
Temperature:	2651°K
θ :	0.025M
$\bar{H}$:	1.32
$\bar{H}_c$:	0.76
δ_c^* :	0.020M
C_f :	0.005
σ :	7.3 Mho/m (Note small σ change through channel)
Ω :	1.05 ($\Omega_{\text{max}} = 1.3$)
B :	1.7T

Recovery pressure:	1.11 atm
Cross section:	0.611(B) x 1.077M(E)
Wall angle:	18° 26'
Output voltage:	3939 Volts
Output power:	11.0 MW
Diffuser efficiency:*	0.85
Exit pressure loss (Region 5)	0.09 atm
Diffuser recovery pressure:	1.02 atm (min 0.98 per Soviet spec.)
Channel exit dimensions:	.620m(B) x 1.171(E)

*

Diffuser recovery is computed using average dynamic pressure at channel exit determined from averaged momentum across total channel cross section.

2.7 Off Design and Other Analysis by STD Research, Inc.

As the preliminary design of the U-25 channel developed, detailed data regarding the design was forwarded to STD Research, Inc. (STD) by MEPPSCO in order that STD might carry out detailed analysis of the design. This data was updated as the design progressed, and STD received specifications of Revisions 1, 2, 4, 5 and 6 (Rev. 6 is referred to as Modification to Rev. 5 by STD). Dr. Craig Maxwell and Dr. A. Kassem of STD have handled the program for STD. In all of this work, STD has acted as an independent OCR contractor, and has not been under contract to MEPPSCO.

The STD calculations which are still in progress have included:

- A. Development of voltage-current (V-I) characteristic.
- B. Analysis of effects of refractory layer on electrodes and determination of current and potential distribution in and near the refractory layer.
- C. Current and potential distribution in the channel ends.

The general interpretive summary of the STD calculations is as follows:

- A. In order to achieve transverse current densities and MHD pressure drop equivalent to those calculated by MEPPSCO. STD has found it necessary to increase the seed concentration so as to achieve a conductivity level approximately 35% greater than that used in the MEPPSCO calculations, but (by 25%) well within the measured conductivity achieved by the U-25 gas generator. The increased seed is necessitated by the higher equivalent electrode drop indicated by the STD calculations.
- B. The STD analysis indicate a more rapid flow acceleration than do the MEPPSCO calculations with transition to low supersonic flow in mid-channel followed by deceleration to a choked exit over the last meter or so. The maximum Mach number for the "design" case is 1.07. Whether, in fact, the actual flow would exhibit a smooth deceleration or a weak shock is not certain (a weak shock seems most likely), and is probably not too important if the Mach number is less than 1.1.
- C. With the STD "design" case taken arbitrarily as having the same inlet conditions as the MEPPSCO design, the seed level and current density adjusted for equivalent j_y and a choked exit with proper recovery pressure, the comparative summaries of the MEPPSCO and STD design performance is given below.

	<u>MEPPSCO</u>	<u>STD</u>
Current	2784 amps	3250
Voltage	3939 Volts	4700
Power Output	11.0 Megawatts	15.5
Conductivity (Inlet)	7.3 Mho/m	9.8

The U-25 gas generator has achieved a conductivity level of 12.5 Mho/m, the higher output predicted by STD analysis may be attributed to:

- A. The increased core power density due to the higher conductivity for equivalent j_y more than compensates for the higher electrode losses that led to the conductivity increase in the first place.
- B. The low supersonic operation over a large part of the channel leads to increased power density. Even more important, however, is the increase in Hall coefficient resulting from the reduced static pressure in the supersonic flow. With the relatively low U-25 field strength and the limited value of ϕ , the increased Hall coefficient will permit substantial improvement in the local turbine efficiency.

As long as the Mach number remains less than 1.15, there should be no concern about supersonic flow since when $M < 1.15$, a shock wave can occur without separation. If a shock rather than a smooth deceleration did occur, as seems likely, there would be some Eddy current losses around the discontinuity. Again, if the shock is weak and not accompanied by separation, the losses should not be of great concern when compared with the improved performance in partially supersonic flow. Thus, we see little reason to modify the loft solely to avoid the low supersonic condition. On the other hand, should it be deemed desirable to keep an entirely subsonic flow, this could easily be provided by a more rapid increase in the d_1 dimension of the loft in the upstream part of the channel while holding the inlet and outlet dimension fixed. This modification would, in fact, ease the mechanical design somewhat, and could easily be accommodated at this stage of the design. We favor the mixed operation in view of the substantially improved performance predicted by the STD analysis.

The STD investigation of the effect of the refractory layer on the electrodes indicate that, at the expected electrode surface temperature (1940°K), the voltage drop due to the refractory will be acceptable if the conductivity lies in the region 10^{-2} to 1 Mho/m. There seems to be little doubt that maintenance material properties can be adjusted to achieve conductivity values in this range. Indeed, the insensitivity to the layer conductivity is very comfortable.

With regard to current and potential distributions in the channel ends, the STD analysis indicates that the upstream power takeoff position suggested by MEPPSCO is about properly placed, but that the position of the downstream takeoff should be slightly downstream from the position suggested. There is no problem since the design provides for complete flexibility in the position of the power takeoff.

Although STD has not completed their analysis of the design, they have kindly provided material describing their analysis to date. Exerpts from this material are included in Appendix 3, for completeness of this report.

SECTION III

PRELIMINARY MECHANICAL DESIGN

3.0 PRELIMINARY MECHANICAL DESIGN

3.1 General Information

Preliminary mechanical design of the magnetohydrodynamic (MHD) channel for the USSR U-25 facility consisted of several major areas, i. e., compatibility interface design between the MHD system and the U-25 facility versus the HPDF, nozzle design, diffuser design, cooling system design, electrode design and channel design. Each of the major design areas will be discussed below.

3.2 Compatibility Design

A comprehensive analysis of drawings and specifications of both the U-25 and the HPDF installations was conducted to determine where dual compatibility questions could arise. This analysis of potential compatibility problem areas was simplified for MEPPSCO due to their extensive prior knowledge of, and familiarity with, the High Performance Demonstration Facility. Dual compatibility questions which required solutions are listed below:

- A. Minimum clearance between the gas side and the HPDF coils is three (3) inches. The minimum clearances between the gas side and the U-25 pole pieces is three and one quarter ($3 \frac{1}{4}$) inches.
- B. Due to the difference in length of the magnets in the U-25 facility and the HPDF, the channel length must be increased by approximately thirty six (36) inches for use in the HPDF.
- C. The external water coolant manifolds are located on the sides of the channel in the U-25 facility and on the channel top and bottom at the HPDF. Further, certain split plates for current density measurement, and plates where pressure taps are located are fed with water at the top and bottom of the plates in both configurations.
- D. A new combustion chamber designed to be operated at the lower pressure appropriate to the U-25 facility will be required at the HPDF.
- E. Continuous room temperature water coolant option should be incorporated into the HPDF magnet.
- F. Modification of the HPDF configuration is required to permit injection of electrode maintenance materials and increase run duration.

- G. Nozzle required to mate with Soviet flange must be modified for HPDF to get the flange clear of the front face of the magnet for attachment to the combustion chamber.
- H. An increase in water flow over that specified by the Soviets to 680 metric tons/hour will be required to assure that the channel cooling system is capable of handling cold wall rates.
- I. Physical modifications will be required in order to shift the channel from the AEDC facility to the U-25 facility.

The actions taken to remove these incompatibilities are discussed in paragraphs 3.2.1 through 3.2.9 below.

3.2.1 Coil Clearance Gap. The external dimensions of the channel system were designed to be compatible with both the HPDF and U-25 coil clearances as indicated in Figs. 1-4 and 1-5. Figure 1-4 (Drawing No. U-25-1293) shows the clearances in the AEDC magnet and Fig. 1-5 (Drawing No. U-25-1299) shows the clearances in the U-25 magnet.

3.2.2 Magnet Length Incompatibility. Due to the greater length of the HPDF magnet, approximately thirty six (36) inches are added to the length of the channel when used in the HPDF. This added length is acquired by insertion of additional frames throughout the length of the channel. These additional frames are indicated in Fig. 1-4 (Drawing No. U-25-1293). Since the frames are dispersed over the entire length of the channel the effect is simply a stretching of the loft.

3.2.3 Coolant Manifolds. The HPDF channel cooling manifold was designed for top and bottom interface. It has an upstream coolant supply and return in the nozzle section, and a downstream top and bottom supply and return for the channel and diffuser. This installation is outlined in Fig. 1-4 (Drawing U-25-1293). Upon removal of the channel assembly from the HPDF, the coolant manifold will be re-oriented to a side mounted position for the U-25. It will then be connected to the nozzle section so that the nozzle, channel, and diffuser may all be cooled from downstream supply and return headers. This installation is outlined in Fig. 1-5. (Drawing No. U-25-1299). Figure 1-6 depicts an artist's concept of the coolant manifold as installed in the U-25 facility.

3.2.4 Combustion Chamber. It is necessary that the HPDF be operated at a pressure lower than that for which it is presently designed in order to be compatible with the lower pressure operation of the U-25. To accomplish this lower pressure operation, a new combustion chamber will be required. The Office of Coal Research was made aware of this requirement in MEPPSCO Progress Report No. 1.

3.2.5 HPDF Magnet Cooling. In order to provide compatibility between the U-25 channel and the HPDF magnet, the option of continuous room temperature water cooling of that magnet is required. The Office of Coal Research was made aware of the requirement for this option in MEPPSCO Progress Report No. 1.

3.2.6 Electrode Maintenance Material Injection. The HPDF was designed for short duration operation, therefore has no provision for injection of electrode maintenance material. To obtain long duration operation electrode maintenance material injection capability must be designed into the new combustion chamber discussed in Paragraph 3.2.4 above.

3.2.7 Nozzle Modification. The nozzle used when the channel is mounted into the U-25 magnet, as outlined in Fig. 3-1 (Drawing No. U-25-1291-Sheet 1) is not long enough to allow the space required to mount the channel in the longer HPDF magnet. For HPDF installation, the nozzle is extended by the addition of rings. This will obtain the necessary clearance at the front of the magnet to allow attachment of the nozzle to the combustion chamber. This modification is reflected in Fig. 3-2 (Drawing U-25-1291, Sheet 2).

3.2.8 Cooling Water Supply. The compromise between regulation of interface temperature and ability to handle cold wall heat load was calculated to assure that failure to slag the channel properly, or loss of slag layer during operation, does not result in catastrophic failure. This assurance can be obtained if the water side of the channel cooling system is capable of handling cold wall rates. Analysis indicated that this required a 25% increase in water flow over that indicated on the original Soviet specifications. A request for an increased water flow resulted in Soviet agreement to increase the flow to a maximum of 680 metric tons/hour. This flow is considered adequate.

3.2.9 Physical Modifications. Upon completion of the test run at AEDC and prior to installation of the channel in the U-25 facility, certain configuration changes must be made. These configuration changes will be:

- A. Removal of additional frames that were required to extend the channel by approximately 36" to accommodate the longer HPDF magnet.
- B. Relocation of the coolant manifolds from the HPDF top and bottom orientation to a side mounted orientation required at the U-25 facility.
- C. Removal of rings from the nozzle, required for the HPDF due to its longer magnet, and installation of the interface to the U-25 combustion chamber.

The configuration changing has been taken into consideration and is expected to be accomplished as a part of the effort of disassembling and packaging depicted in Blocks 89 and 90 of the U-25 Channel Master Schedule.

3.3 Nozzle and Diffuser Design

3.3.1 General Information. Due to the fact that the nozzle and diffuser design are relatively straightforward as compared to the channel, their design will be discussed in Paragraphs 3.3.2 and 3.3.3 below.

3.3.2 Nozzle Design. The nozzle is designed for cold wall gas side heat loads. It is composed of a series of water cooled copper frames. The water passages will be machined into the frames, then the water passages will be sealed by brazing copper material over the passages. After brazing, the interior faces of the frames will be further machined to provide the gas side subsonic expansion contour. After the second machining operation the frames will be bolted together with "O" ring seals between each frame to prevent leakage of gases. As with other components of the channel system, bolted construction is used to allow disassembly and modification. The frame construction is the same as that successfully employed with the LORHO Pilot and which will be employed with the High Performance Channel at AEDC. The design minimizes problems with thermal stresses.

The magnet used in the HPDF is longer than the one used in the U-25 facility, therefore provision must be made in the U-25 channel system to accommodate this difference when the channel system is to be installed at the HPDF. This has been accomplished in the design by the addition of frames to the nozzle. The addition of these frames to the front of the nozzle moves the nozzle flange far enough away from the front of the magnet to allow adequate clearance for attaching the nozzle to the combustion chamber.

Figure 3-1 (Drawing No. U-25-1291 Sheet 1) shows the nozzle as configured for the U-25 installation. Figure 3-2 (Drawing No. U-25-1291 Sheet 2) shows the modification of the nozzle for installation in the HPDF.

3.3.3 Diffuser Design. The diffuser, also designed for cold wall gas side heat loads, is a tapered rectangular cross section pressure vessel constructed of copper. It is a double wall structure composed of an outer and inner wall. The outer wall will be made up of flat plates suitably reinforced which will be joined at the four corners with longitudinally welded sections of tubing. The walls and reinforcing members were selected to support the structural loads imposed upon a vacuum chamber. The diffuser will be operated at a negative eight (-8) psi, or eight psi below atmospheric pressure and also at the loads imposed by the boiling suppression pressure of the cooling water. A series of expansion joints are

located axially along its length to allow for the differential expansion between the inner and outer wall caused by the heat of the combustion gases.

The inner wall will consist of a series of thin formed plates which are intermittently welded to the outer wall and continuously welded to each other, essentially forming rectangular shaped water cooling passages. These plates are welded into the structure in the flat condition. After thermal stress relieving of the structure it is pressurized at which time the plates are deformed into radius. See Fig. 3-3 for an illustration of this deformation.

Fig. 3-3 . Pressure Forming of Coolant Passages

Under applied thermal loads these thin sections behave as membranes with only tension forces (no bending moments) while deflecting cylindrically due to the cooling water pressure in the axial direction of the diffuser. This membrane is able to compensate for thermal expansion in one direction only. The other direction is compensated for by the expansion joints in the outer wall. Figures 3-4 through 3-6 (Drawings U-25-1292-1, 2 and 3) show details of diffuser construction.

3.3.4 Interface to U-25 Combustion Chamber and Diffuser. Interface drawings showing the U.S. flange and bolt layout to mate up to the Soviet combustion chamber and steam generator have been prepared and are given in Figs. 3-7 and 3-8. The views are looking at the U.S. flanges. The interface drawings have been prepared from facility drawings supplied by the Soviets. The interface drawings were transmitted to the Soviets on 15 October 1974.

3.4 Cooling System Design

3.4.1 General Information. An analysis of the cooling system has been carried out to verify the basic integrity of the design and to determine that the cooling water supplied by the Soviets will be adequate. The specifications for the coolant supply are given in Table 3.4-1 below. Two sets of figures are presented. One set is the data originally provided by the Soviets in July 1973, while the second set of data is modifications agreed to by the Soviets in October 1974. These

III-8

MEPPSCO, INC.	
Fig. 3-4 Diffuser	PUBA
3-3074 U-25-1292-1

SECTION B-B

SECTION C-C

SECTION F-F
SCALE 1/2" = 1"

SCALE 1/2" = 1"

NOTE 1 WELD TO BE OMITTED OVER EXPANSION JOINTS SHOWN IN DETAIL Z.
2. TO BE WATER PRESSURE TESTED TO 200 PSIG

TOLERANCES		MEPPSCO, INC.	
UNLESS OTHERWISE SPECIFIED		DATE	1/1/68
GENERAL		BY	W. J. W.
FUNCTIONAL		CHECKED BY	W. J. W.
ASSEMBLY		APPROVED BY	W. J. W.
FIG. 3-5 Diffuser		U-25-1632-2

14	BOSS	ST. STL.	36
13	INLET FLANGE .50 THK	ST. STL.	1
12	INLET FLANGE .50 THK	ST. STL.	4
11	INLET FL .50 THK	ST. STL.	1
10	1" SCH 40 PIPE	ST. STL.	48
9	INNER LINER .104 THK	ST. STL.	66
8	OUTER LINER .38 THK	ST. STL.	6
7	SUPP 2.00x1.25	ST. STL.	5
6	EXP. JOINT 3.25 O.D. 25 WALL	ST. STL.	6
5	CAVITY .50 THK	ST. STL.	4
4	CAVITY .50 THK	ST. STL.	2
3	COVER .50 THK	ST. STL.	4
2	COVER .50 THK	ST. STL.	1
1	FLANGE	ST. STL.	1
ITEM	DESCRIPTION		QTY

MEPPSCO, INC.	
Fig. 3-6 Diffuser	830-74 U-25-1292-3

MEPPCO, INC.			
TOLERANCES (EXCEPT AS NOTED)			
DECIMAL 00 = .010 000 = .005		SCALE 1" = 10"	DRAWN BY J. CHANLER
Fig. 3-7	TITLE INTERFACE @ STA-47.0 COMBUSTION CHAMBER TO NOZZLE		
ANGULAR	DATE 9 OCT 74	DRAWING NUMBER U25-1310	APPROVED BY

Fig. 3-8	INTERFACE @ STA. 314.41 U.S. DIFFUSER TO SOVIET DIFFUSER
10-10-74	U-25-1311

modifications have the effect of providing increased cooling water flow at somewhat lower pressure.

TABLE 3.4-1

U-25 COOLANT SUPPLY SPECIFICATIONS

	<u>Original</u>	<u>Modification</u>
	7/73	10/74
Cooling Medium	water - demineralized	water
Flow Rate	560 metric tons/hour	680 metric tons/hour
Pressure at Inlet	50 atm abs (735 psia)	40 atm abs (588 psia)
Temperature at Inlet	40°C	40°C
Temperature at Outlet	100°C	100°C

When necessary, there can be blown air with the following parameters fed into the channel:

Temperature:	77°C
Pressure	to 6 abs atm
Mass Flow	to 2 kg/sec

During meetings in October 1973 and February 1974, the Soviets stated that it would be desirable that all of the U.S. equipment should be cooled with the water flow shown on the original specification, but that should larger amounts of water be required they should be notified as soon as possible in order that this additional flow could be provided. Notification of increased flow requirements was given, and the Soviets agreed to provide the amount reflected in the modified column of Table 3.4-1. It should be noted that in the case of the Soviet channel system only part of the diffuser is cooled with the channel cooling system while the remainder is on the same system as the combustion chamber; the Soviets were not satisfied with this arrangement.

Analysis of the cooling system is divided into three major components: nozzle, chamber, and diffuser. Forced convection water side heat transfer only is used for all components. There is no reliance on nucleate boiling.

3.4.2 Gas Side Heat Load. In an MHD channel, the wall is rough due to segmentation, refractory, etc., and the flow is in the completely rough regime, with

$$R_{cr} = \frac{K_s}{\nu} \sqrt{\frac{\tau_w}{\rho}}$$

well above 70; K_s is the roughness height, ν the kinetic viscosity, τ_w the wall shear, and ρ the fluid density. The fact that the wall is cooler than the stream increases the effective size of the wall protrusions. The flow is compressible, and at high subsonic or low to moderate supersonic Mach number, the ratio of the stream total enthalpy, h_s , to the wall enthalpy, h_w , may vary from near unity to as low as 0.1, depending on the generator design location in a particular generator and electrode or insulating wall. Due to the relatively short length/diameter ratio, the flow is not fully developed as in a long pipe but resembles a turbulent flow over a flat plate with pressure gradient.

The usual Reynolds analogy does not apply to a rough wall since there is momentum loss from eddies as well as shear. W. Nunner⁽⁵⁾ has attempted to extend Reynolds analogy to a rough wall in the case of pipe flow. His expression for the Stanton number in this circumstance is:

$$St \approx \frac{1}{2} C_f \left\{ 1 + 1.5 R_e^{-1/8} Pr^{-1/6} \left[Pr \frac{C_f}{C_{fo}} - 1 \right] \right\}^{-1}$$

where Pr is the Prandtl number, C_f is the rough wall friction coefficient and C_{fo} is the friction coefficient for a smooth wall in the same pipe. Although not clearly evident from this relationship, Nunner's formula gives an approximate dependence such that $St \sim \sqrt{C_f}$ for Prandtl numbers of the order of 0.8. Nunner's experiments utilized a type of roughness particularly appropriate to an MHD generator; that is, ridges perpendicular to the flow direction and generally verified in the predicted form. The general dependence which places the heat transfer rate approximately proportional to the square root of the friction coefficient in the completely rough regime is corroborated by a number of investigators^(6, 7, 8) for the case of Prandtl numbers near unity. Perhaps the best experimental evidence in the literature is Sams,⁽⁷⁾ whose Fig. 13 is attached as Fig. 3-9. In this figure, the friction velocity, V_t , is given by:

$$V_t = \sqrt{\frac{\tau_w}{\rho}} \sim \sqrt{C_f}$$

Fig. 3-9. Correlation of Heat Transfer Data with Modified Film Reynolds Number and Friction Velocity.

It is seen that all of the data for Reynolds numbers based on friction velocity greater than about 500 and rough walls are correlated by the equation which places $St \sim \sqrt{C_f}$.

An exception to $St \sim \sqrt{C_f}$ seems to be the work of Pope⁽⁹⁾ who reports that roughness affects the heat transfer but very little.

None of the references cited here was carried out under circumstances identical with those of an MHD generator. In general, the Mach number used by the investigators was low; dissociation was not a factor, and wall heating was involved rather than wall cooling. However, the correspondence between these investigations cited (with the exception of Pope) and the wide disparity in their test conditions does suggest that these results will have some general validity.

Since the flow in the MHD channel is not fully developed, the friction coefficient can be arrived at only by indirect means, such as agreement with experimental data in the presence of MHD effect in the case of generators with large interaction, stream momentum surveys, etc. Heat transfer can be measured by measuring the flow rate and temperature rise in the cooling water but there does not appear to have been a systematic investigation of these effects.

In the LORHO generator, the experimental performance data best correlates with a friction coefficient approximately three times that of a flat plate. The friction coefficient influences the pressure distribution in the channel as well as the performance of the diffuser. Nonetheless it should be realized that the factor of three was arrived at by indirect means. However, inspection of the channel wall would lead one to imagine that the factor of three was not inconsistent for the Mach 2.5 LORHO flow. In fact, the general form of the roughness is such that one would expect large friction coefficients. The LORHO generator is the only one where simultaneous heat transfer measurements and friction coefficient estimates are available. The heat transfer measurements were not extensive and were only taken to assure the integrity of the design; that is, to make certain that the cooling was adequate. The predicted heat transfer rates are uncertain due to the uncertainty in the inlet Reynolds number and the effective MHD pressure gradients in the channel, as well as the uncertainty in the wall enthalpy. The rates which have been observed are approximately of the same order or slightly less than those which would be expected from a smooth wall under the same conditions.

In the case of the ring type Hall channels tested at the Long Duration Test Facility, no estimate of the friction coefficient was obtained, but the general character of the roughness is the same as in the LORHO; that is to say, such that one might expect a friction factor of twice that of a smooth wall. The observed heat transfer rates here appeared to be about 20% higher than one would expect from the smooth wall under the same circumstances.

Perhaps the best experimental indication of the influence of roughness in an actual MHD situation is taken from Reference 10, shown as Fig. 3-10, and shows the mean heat transfer data for two peg wall channels (S/N1 and S/N2) with rough walls typical of the MHD channel, and a relatively smooth wall (S/N3). For comparison, the predicted heat transfer assuming a smooth fully developed pipe flow, as well as a smooth flat plate with a Reynolds number appropriate to mid-channel is shown. The latter is most appropriate since the flow is not fully developed. It is seen that the data for S/N1 and S/N2 are about 30% above the smooth flat plate value, while the smooth wall data with S/N3 are in good agreement with the expected value.

The rough pipe correlation of Sams⁽⁷⁾ has been modified for a flat plate. Sams' correlation equation⁽⁷⁾ is:

$$\frac{h_f D}{K} = 0.040 \left(\frac{\rho V_t D}{\mu} \right)^{1.0} \left(\frac{\mu C_p}{K} \right)^{0.4}$$

where

h_f = the film heat transfer coefficient

D = pipe diameter

K = fluid thermal conductivity

μ = fluid viscosity

C_p = fluid specific heat

ρ = fluid density

V_t = "friction velocity" = $\sqrt{T_w/\rho}$

Fig. 3-10. Heat Transfer Measurements of Water Cooled Peg Walls

Advanced Energy Conversion 5, 100 (1965).

where

$$T_w = \text{wall shear} = (1/2) \rho U^2 C_f$$

and

$$C_f = \text{wall friction coefficient}$$

As usual, to transfer fully developed pipe data to a plate, we put $D = 2\delta$, with δ the boundary layer thickness; even this is not necessary in this case since the explicit dependence on D cancels out. Computing $\dot{q}$, the heat transfer rate, we find

$$\dot{q} = h_f (T_s - T_w) = 0.040 \frac{K}{D} \left(\frac{\rho V_t D}{\mu} \right)^{1.0} \left(\frac{\mu C_p}{K} \right)^{0.4} C_p (T_s - T_w)$$

where T_s and T_w are the stagnation and wall temperatures, respectively. The dependence on D cancels and inserting the expression for V_t gives

$$\dot{q} = .040 \left(\frac{K}{\mu C_p} \right)^{0.6} \sqrt{\frac{C_f}{2}} \rho U C_p (T_s - T_w)$$

The Sams' data are taken for fluids with constant specific heat. In the usual manner for applying heat transfer data for perfect fluids to reacting mixtures, put

$$C_p (T_s - T_w) \equiv h_s - h_w$$

where h_s and h_w are the stream total and wall enthalpies, respectively. Then

$$\dot{q} = .040 \text{Pr}^{-0.6} \left(\frac{C_f}{2} \right)^{0.5} \rho U (h_s - h_w)$$

where Pr is the Prandtl number. So, for the fully rough wall:

$$\text{St} = \frac{\dot{q}}{\rho U (h_s - h_w)} = .040 \text{Pr}^{-0.6} \left(\frac{C_f}{2} \right)^{0.5}$$

where St is the Stanton number, is the equivalent of Reynolds analogy for the fully rough wall. For the smooth wall:

$$\text{St} = (\text{Pr})^{-2/3} \left(\frac{C_f}{2} \right)$$

Both expressions for C_f are plotted in the attached Figure 3-11. It is clear that for rough walls, Stanton numbers computed using the usual Reynolds analogy for smooth walls and rough wall friction coefficients overestimate the heat transfer rate. This is in accord with MHD experience.

The clean combustion gases have a low f-number so that radiation heat transfer is small compared with the convective and electrical in the near sonic flow at high pressure.

3.4.3 Cooling System Design Criteria. Since electrode replenishment material will be added to the combustion chamber and is likely to roughen the walls in all components, the Stanton number for gas side heat load is given by:

$$St = .040 Pr^{-0.6} \left(\frac{C_f}{2} \right)^{0.5} \pm 15\% \text{ (fully rough)}$$

where St is the Stanton number, Pr is the Prandtl number, and C_f is the friction coefficient.

In order to provide positive assurance of cooling system integrity, it is desirable that all components should be designed for cold wall gas side heat loads, in spite of the fact that the refractory coating will reduce the heat load substantially, particularly for the channel. The nozzle and diffuser are designed for cold wall gas side heat loads. However, some compromise must be made with the channel since it is not possible simultaneously to handle cold base metal and refractory electrode for current transfer. That is to say, if cold wall rates are assumed and the water passage is placed properly to accept these rates, the interface temperature will be too low for current transfer when the hot walls that are characteristic of electrode maintenance are obtained. On the other hand, if hot walls are assumed with the interface designed at a high temperature for efficient current transfer and the channel is not slagged properly, the gas side metal surface will overheat. Thus, it is essential that the channel be properly slagged before the heat load is increased to the maximum value and the electrical dissipation heat load that occurs during power generation is applied.

The situation is not unlike that encountered in conventional boilers where the design is dependent on certain parts of the boiler surface being covered with an insulating oxide layer. The boiler cannot be fired at full heat rate until the slag layer is established or when any operating circumstance has removed the slag layer. In the case of the MHD channel, the proper preparation of the surface is facilitated by:

Fig. 3-11. St vs C_f for Rough and Smooth Walls.

- A. Reduction of the electrode heat load during operation without power generation when the electrical heat transfer due to boundary layer dissipation is not present.
- B. The material initially installed in the electrode can be selected to glaze the surface under reduced firing conditions so as to provide a protective layer.
- C. The U-25 (and AEDC) combustion chamber can be fired at flow rates sufficiently low that a fully subsonic flow without power generation can be used to prepare the wall.

An additional gas side heat transfer over and above the convective is associated with the electric dissipation in the boundary layer. The conservative approach is to count all of this boundary layer dissipation as heat transfer to the electrode wall. Thus for the electrode walls an additional heat transfer rate:

$$\dot{q}_e = 1/2 V_e j_y$$

is assigned.

The 50 kg/sec heat load to the electrode and slant walls, respectively is shown in Fig. 3-12. For flow rates less than 50 kg/sec, the convective heat load equal to that on the slant walls may be taken proportional to flow rate. It is seen that the electrode heat load becomes the major heat load towards the back of the channel. Also to be noted is the relative uniformity of the heat load to the electrode wall. This is due to the increased electrode voltage drop caused by the thick boundary layer toward the back of the channel compensating for the reduction in convective load due to reduced mass flux.

The water side heat load per unit length of frame is equal to the product of gas side heat load by the width of frame exposed to the gas as indicated in Fig. 3-13. Width of frame plus insulation thickness, t , and local value of $E_y/E_x = \phi$, the exposed widths on slant and electrode walls respectively, t_s and t_e is:

$$t_s = t$$

$$t_e = t \sqrt{1 + \phi^2}$$

Note that t is different on the two electrode walls for a tapered frame. This must be accounted for. Thus, the increased heat transfer to the electrode walls due to Joule dissipation in the boundary layer is magnified at the water side by the fact that a greater width is exposed to the gas on the electrode wall. Further, $|\phi|$ is decreasing with increasing x in the active region of the channel, so that the exposed area is maximum on the upstream or higher heat transfer end of the

Fig. 3-12. Heat Transfer Across Channel Cooling Section.

Fig. 3-13. Sketch Illustrating Heat Transfer in Frame

plate, and must be accounted for in the analysis of local cooling conditions. However in the electrode wall, the preliminary analysis indicates that bulk rise rather than boiling suppression will be controlling. This is to be expected with the small water passage size (0.187"), long run, high velocity and high pressure drop in the frames. Thus for estimation of water flow requirements, the mean heat transfer rate at the point where the frame crosses the center line can be used.

The compromise between regulation of interface temperature and ability to handle cold wall heat load should be accomplished in such a way that failure to slag the channel properly, or loss of the slag layer during operation, does not result in a catastrophic failure. This can be assured if the water side of the channel cooling system is capable of handling cold wall rates. For this to be accomplished, a 25% increase in water flow over that originally specified by the Soviets will be required. It was for this reason that the increase in water flow was requested.

3.4.4 Summary of Gas Side Heat Load and Adequacy of Coolant Supply. The heat transfer rate to the nozzle is shown on Fig. 3-16 and to the diffuser on Fig. 3-20.

By using the gas side loft, the total heat input to a component, Q , can be calculated from:

$$Q = \int 2(d_1 + d_2) \dot{q} dx$$

When this is done, the results are as follows for a cold wall assumption:

Nozzle	2.31 MW
Channel	35.63 MW
Diffuser	<u>4.14 MW</u>
Total	42.1 MW

Assuming a 60 °C water bulk temperature rise, the required coolant flow is 603 m³/hour. At a mass flow rate of 680 metric tons/hour, the maximum potential heat absorption condition would be 47.5 MW. Thus at 50 kg/sec, mass flow, the overall safety factor for cold wall is 13%. This is considered adequate in view of the fact that the cold wall assumption is a worst case condition in the first place.

3.4.5 Component Water Side Analysis. Basic analysis of all three components is similar. In the case of the nozzle and channel, the component is broken down into a number of frames; eight in the case of the nozzle and over five hundred in the case of the channel. The water flow to each of the frames in the nozzle and channel can be calculated by simply computing the heat input to the frame and assuming a 60°C rise for the water. It is then necessary to check that local heat transfer conditions are satisfactory to prevent local boiling.

For all components, the heat transfer coefficient h_t is given in the standard form by:

$$h_t = \frac{\dot{q}}{\Delta T_f}$$

$$h_t = .023 \frac{K}{D_n} R_e^{0.8} P_r^{1/3}$$

which for water with $P_r = 1.45$ and $K = .396 \text{ Btu/hour ft } ^\circ\text{F}$ (250^oF) becomes

$$h_t = .010308 \frac{R_e^{0.8}}{D_n}$$

where

K = thermal conductivity

D_n = hydraulic diameter

R_e = Reynolds number

P_r = Prandtl number

From the equation above, the temperature drop across the film can be calculated with the assumed flow giving the 60^o rise.

Because the equipment is designed for long duration operation, a fouling factor, r , of 0.0002 Btu/hour ft² °F has been used for all of the components. The local maximum film temperature T_f is given by:

$$T_S = T_b + T_f$$

and the metal temperature, T_M , is given by:

$$T_M = T_f + \dot{q} r$$

Note that the $\dot{q}$ in the above is not necessarily the same as the $\dot{q}$ on the gas side. Each case is considered separately on the basis of the relationship between gas side and water side heat transfer area. This is particularly important for the angled frames in the channel.

Knowing the maximum film temperature at every station in the cooling circuit of an individual component, the boiling suppression pressure can be determined from the steam tables. It is necessary to ascertain that these boiling suppression pressures can be taken by the individual component structurally and can be provided by the cooling system when the pressure drop through the components is taken into account.

3.4.6 Component Pressure Drop. The pressure drop Δp in an individual component is given by:

$$\Delta p = \Delta p_f + \Delta p_s$$

For Δp_f is the pressure drop due to pipe friction and Δp_s is the pressure drop due to such factors as curves and bends. The friction drop Δp_f is given by:

$$\Delta p_f = 1/2 \rho u^2 f L/D_n$$

where

$$1/2 \rho u^2 = \text{dynamic}$$

$$f = \text{fanning factor}$$

$$L = \text{length of run}$$

The hydraulic diameter needs to be computed for each situation. The shape drop Δp_s is estimated by assigning equivalent length/diameter ratios to the various shapes that are encountered. The most important of these is the short radius elbow for which an L/D factor of 30 is assigned.

3.4.7 Results of Cooling System Analysis. As stated in Paragraph 3.4.5 above, once all of the parameters have been established, the analysis of cooling for each of the major components, i. e., nozzle, channel and diffuser is relatively the same. For purposes of clarity, the results of analysis for each major component will be presented on tables for that component in Paragraphs 3.4.7.1 through 3.4.7.3, starting with the nozzle. Figure 3-14 shows a typical connection of the water cooling manifold to the channel. Note that each frame will have two inlet and two return connections. One inlet will channel water to the cooling passage across the top of the frame and the other will channel water across the bottom to assure elimination of hot spots. All heat loads have been calculated both for the "normal" cold water flow of 600 tons/hr and an "emergency" heat load which assumes a gas side heat transfer adequate to heat 680 tons/hr to 100°C.

3.4.7.1 Before looking at the specifications of nozzle cooling, check Fig. 3-15 to obtain a clear picture of the nozzle water channel configuration.

Fig. 3-14. Typical Manifold to Channel Water Connection

Side Walls

Frame 8: $B = 1.3125''$
 Other frames: $B = 0.81''$
 Area = $2 \times 0.25 B \text{ in}^2$.

Top & Bottom Walls

Side wall B values are larger, however calculations use above values in a conservative way.

Fig. 15 Typical Nozzle Water Passage Configuration.

Fig. 3-16. Heat Transfer Across Nozzle Cooling Section

The graph illustrated in Fig. 3-16 was derived from the tables discussed below. Table 3.4-2 indicates the formula for calculation of heat transfer area exposed to gas flow and the use of $\dot{q}$ values to calculate heat dissipation of each nozzle frame.

TABLE 3.4-2

NOZZLE HEAT TRANSFER CALCULATIONS

Heat input formula: $\dot{q} \times \frac{A_1}{A} = \frac{\text{Watts}}{\text{cm}^2}$

Where A_1 is the smallest gas flow area, and A the heat transfer surface area exposed to gas flow. Using the above formula, the physical dimensions of the nozzle, and a $\dot{q}$ value of 301.5 and 338 for nozzle heat losses of 2.309 and 2.604 MW respectively, the heat dissipation of each nozzle frame was calculated as shown below, for the normal operating flow of 600 m³/hour and the emergency flow of 680 m³/hour.

FRAME	A_1/A Average	FRAME HEAT TRANSFER AREA, in ²	600 m ³ /hr.		680 m ³ /hr.	
			$\dot{q}$ Watts cm ²	Q MW	$\dot{q}$ Watts cm ²	Q MW
1	.4945	242.18	149	.233	167	.261
2	.5675	219.10	171	.242	192	.271
3	.6455	202.81	195	.255	218	.285
4	.725	189.04	219	.267	245	.299
5	.803	178.68	242	.279	271	.313
6	.876	171.40	264	.292	296	.327
7	.9365	165.55	282	.302	317	.338
8	.9815	259.37	296	.495	332	.555

Allowing a cooling water temperature increase of 60°C and with cooling passage dimensions as shown in Fig. 3-15, the resulting water velocities and flow rates are shown in Table 3.4-3 below.

TABLE 3.4-3
COOLANT VELOCITY AND FLOW RATES

FRAME	<u>600 m³/hr</u>		<u>680 m³/hr</u>	
	V FPS	G GPM	V FPS	G GPM
1	11.34	14.38	12.85	16.30
2	11.78	14.94	13.35	16.93
3	12.40	15.73	14.05	17.83
4	12.98	16.46	14.71	18.65
5	13.59	17.23	15.40	19.53
6	14.22	18.04	16.12	20.45
7	14.69	18.63	16.65	21.11
8	14.93	30.60	16.92	34.68

The total pressure drop across each nozzle frame is indicated in Table 3.4-4 for a flow rate of 600 m³/hr and Table 3.4-5 for a flow rate of 680 m³/hr. These tables are preceded by a brief discussion of the formula used in their preparation.

Water properties at an average boundary layer temperature of 250°F were used to allow calculation of flow regime and pressure drops:

$$\rho = 58.8 \text{ lbs/ft}^3$$

$$\nu = .269 \times 10^{-5} \text{ ft}^2/\text{sec}$$

$$k = .396 \text{ Btu/hr ft } ^\circ\text{F}$$

$$\text{Pr} = 1.45$$

For Frame 8:

$$D_H = 4 \times \frac{.5B}{144} \times \frac{12}{2(B+.25)} = .035 \text{ Ft.}$$

And all other frames:

$$D_H = .032 \text{ Ft.}$$

The flow regime is turbulent as indicated by high Reynolds numbers. Assume the presence of six (6) elbows at $L/D_H = 30$ each.

From Moody's graph⁽¹¹⁾ for pipe flow considering an appropriate roughness factor:

$$\text{Frame 8: } f = .029$$

$$\text{Other frames : } f = .0298$$

TABLE 3.4-4

PRESSURE DROP FOR FLOW RATE OF 600 m³/hr

FRAME	$\frac{\rho V^2}{2g} = P_V$ psi	L, ft	$f \frac{L}{D_H} P_V$ psi	6 Elbows psi	TOTAL PRESSURE DROP, psi
1	.82	8.7	6.6	4.4	11.8
2	.88	8.2	6.7	4.7	12.3
3	.97	7.8	7.0	5.2	13.2
4	1.07	7.5	7.5	5.7	14.3
5	1.17	7.2	7.8	6.3	15.3
6	1.28	7.0	8.3	6.9	16.5
7	1.37	6.9	8.8	7.3	17.5
8	1.41	6.8	7.9	7.4	16.7

TABLE 3.4-5

PRESSURE DROP FOR FLOW RATE OF 680 m³/hr

FRAME	$P_V = \frac{\rho V^2}{2g}$ psi	$f \frac{L}{D_H} P_V$ psi	6 Elbows psi	TOTAL PRESSURE DROP, psi
1	1.05	8.7	5.6	15.4
2	1.13	8.6	6.1	15.8
3	1.25	9.8	6.7	17.8
4	1.37	10.3	7.4	19.1
5	1.50	10.1	8.1	19.7
6	1.65	10.8	8.9	20.6
7	1.76	11.3	9.5	22.6
8	1.82	10.3	9.5	21.6

The nozzle water boundary layer ΔT is shown in Table 3.4-6 for flow rates of both 600 m³/hr and 680 m³/hr.

TABLE 3.4-6

NOZZLE WATER BOUNDARY LAYER ΔT

FRAME	600 m ³ /hr				680 m ³ /hr			
	R_e	h	Q	ΔT	R_e	h	Q	ΔT
		$\frac{\text{Btu}}{\text{hr ft}^2}$	$\frac{\text{Btu}}{\text{hr ft}^2}$	$^{\circ}\text{F}$		$\frac{\text{Btu}}{\text{hr ft}^2}$	$\frac{\text{Btu}}{\text{hr ft}^2}$	$^{\circ}\text{F}$
1	135000	4093	472446	116	152900	4524	529500	117
2	140000	4220	542203	129	158800	4664	608800	131
3	147500	4397	618302	141	167100	4859	691230	143
4	154400	4560	694400	152	175000	5040	776840	154
5	162000	4731	767329	162	183200	5229	859300	164
6	169000	4906	837086	170	191762	5423	938550	173
7	174700	5035	894160	178	198000	5565	1005100	181
8	194200	5010	938551	188	220150	5538	1052700	190

Note the small variation in ΔT at both flow rates. The highest water boundary layer temperature is at the flow exit where the bulk water temperature is maximum.

The water pressure required at the inlet of each nozzle frame is indicated in Table 3.4-7. It is the sum of the water pressure drop at the frame exit plus the boiling suppression pressure.

TABLE 3.4-7
NOZZLE FRAME INLET PRESSURE REQUIREMENTS

FRAME	MAX. FILM TEMP. °F	BOIL SUPP. psig	INLET PRESSURE psig	
			@600 m ³ /hr	@680 m ³ /hr
1	212 + 117 = 329	87	99	103
2	212 + 131 = 343	108	121	124
3	212 + 143 = 355	128	142	146
4	212 + 154 = 366	151	166	170
5	212 + 164 = 376	171	187	191
6	212 + 173 = 385	193	210	214
7	212 + 181 = 393	214	232	237
8	212 + 190 = 402	240	257	262

The temperature in the heat transfer wall must be known in order to calculate thermal expansion and thermal stresses, which are discussed in Paragraph 3.5 of this report. Nozzle heat transfer wall temperatures are indicated in Table 3.4-8. Because the equipment is designed for long duration operation a fouling factor of 0.0002 is included in the calculation. This modifies the overall heat transfer coefficient as follows:

$$\frac{1}{U} = .0002 + \frac{1}{h}$$

in other words, the fouling factor represents a second thermal barrier with a film coefficient of:

$$\frac{1}{.0002} = 5000 \frac{\text{Btu}}{\text{hr. ft}^2 \text{ } ^\circ\text{F}}$$

TABLE 3.4-8

NOZZLE HEAT TRANSFER WALL TEMPERATURES

FRAME	600 m ³ /hour				680 m ³ /hour			
	$\Delta T, ^\circ F$ Fouling	$\Delta T, ^\circ F$ Inside Wall	$\Delta T, ^\circ F$ Copper	$\Delta T, ^\circ F$ Outside Wall	$\Delta T, ^\circ F$ Fouling	$\Delta T, ^\circ F$ Inside Wall	$\Delta T, ^\circ F$ Copper	$\Delta T, ^\circ F$ Outside Wall
1	94	423	44	467	106	435	49	484
2	108	451	50	501	122	465	56	521
3	124	479	57	536	138	493	64	557
4	139	505	64	569	156	522	72	594
5	154	530	71	601	172	548	79	627
6	167	552	77	629	188	573	87	660
7	179	572	83	655	201	594	93	687
8	188	590	87	677	211	613	97	710

3.4.7.2 Before considering the specifics of channel cooling, refer to Fig. 3-17 to obtain a clear picture of the channel cooling water passage configuration.

Fig. 3-17. Typical channel frame water passage configuration.

Figure 3-18 is a graphic illustration of heat transfer across the channel cooling section from 0.00 meters to 7.00 meters. The graph illustrated in Fig. 3-18 was derived from the tables discussed below:

Table 3.4-9 indicates the physical data for the channel frames upon which all channel cooling water calculations are based.

TABLE 3.4-9
CHANNEL FRAMES PHYSICAL DATA

FRAME STATION m	"SLANTED" l_1 , inch	"ELECTRODE" l_2 l_3		ϕ DEGREES	AXIAL LENGTH $l_1 \sin \phi$, m	STATIC PRESSURE psig
.15	31.3	10.6	13.0	22.25	.301	10.8
.4	33.1	13.8	13.2	29.63	.589	10.2
.857	37.9	14.7	13.7	40.60	.626	9.1
1.4	45.6	15.6	14.3	50.18	.889	7.8
3	44.3	17.2	16.4	43.55	.776	4.0
4	44.2	18.9	17.6	38.48	.699	1.5
5	44.3	20.5	18.7	32.60	.607	-.8
6	45.6	23.7	22.4	26.57	.516	-3
6.4	44.4	24.3	23.7	17.20	.334	-4
6.95	46.1	24.4	24.4	0	0	-5.5

Fig. 3-18. Heat Transfer Across Channel Cooling Section

Table 3.4-10 indicates heat transfer across selected frames of the channel. Due to the large number of frames involved, frames at different stations throughout the channel were chosen as representative samples. Heat transfer rates are given for both the 600 m³/hour and the 680 m³/hour flow rates.

TABLE 3.4-10

HEAT TRANSFER ACROSS CHANNEL FRAMES

FRAME STATION m	600 m ³ /hour				680 m ³ /hour			
	Q _E	Q _S	Q _E	Q _S	Q _E	Q _S	Q _E	Q _S
	FRAME MW	FRAME MW	FT MW	FT MW	FRAME MW	FRAME MW	FT MW	FT MW
.15	.0206	.0439	.0105	.0084	.0233	.0498	.0119	.0095
.4	.0238	.0464	.0106	.0084	.0270	.0526	.0120	.0095
.857	.0301	.0518	.0127	.0082	.0341	.0587	.0144	.0093
1.4	.0354	.0519	.0142	.0068	.0401	.0588	.0161	.0077
3	.0341	.0439	.0122	.0059	.0386	.0498	.0138	.0067
4	.0350	.0386	.0115	.0052	.0397	.0437	.0130	.0059
5	.0353	.0323	.0108	.0044	.0400	.0366	.0122	.0050
6	.0318	.0300	.0083	.0039	.0360	.0340	.0094	.0044
6.4	.0236	.0232	.0059	.0031	.0267	.0263	.0067	.0035
6.95	.0121	.0193	.0030	.0025	.0137	.0219	.0034	.0028

Table 3.4-11 indicates the coolant velocity, pressure drop and flow rates across the frames for a 600 m³/hour flow. This chart is based upon a two pass flow through each frame.

TABLE 3.4-11

600 m³/hr. COOLANT VELOCITY, PRESSURE DROP AND FLOW RATES

FRAME STATION m	$\frac{Q_E + Q_S}{2}$ MW	$\frac{L = 2l_1 + l_2 + l_3}{2}$ ft	V fps	$\frac{\rho V^2}{2g} = P_v$ psi	$f \frac{L}{D} = P_v$ psi	4 Elbows psi	TOTAL PRES- SURE DROP psi	GPM PER PASS
.15	.03225	3.59	14.6	1.35	9.7	5.9	17	2.08
.4	.0351	3.88	15.9	1.60	12.4	6.9	21	2.27
.857	.04095	4.34	18.6	2.18	18.9	9.4	31	2.64
1.4	.04365	5.05	19.8	2.48	25.0	10.7	38	2.82
3	.0389	5.09	17.6	1.97	20.1	8.5	31	2.51
4	.0368	5.21	16.7	1.76	18.3	7.6	28	2.38
5	.0338	5.33	15.3	1.49	15.9	6.4	24	2.18
6	.0309	5.72	14.0	1.24	14.2	5.4	21	1.99
6.4	.0234	5.70	10.6	.72	8.2	3.1	12	1.51
6.95	.0157	5.88	7.1	.32	3.8	1.4	6	1.01

Table 3.4-12 indicates the coolant velocity, pressure drop, and flow rates across the frames for a 680 m³/hour flow. This chart is also based upon a two pass flow through each frame.

TABLE 3.4-12

680 m³/HR. COOLANT VELOCITY, PRESSURE DROP AND FLOW RATES

FRAME STATION m	$\frac{Q_E+Q_S}{2}$ MW	$\frac{L=2l_1+l_2+l_3}{ft^2}$	V fps	$\frac{\rho V^2}{2g}$ psi	$= P_v$	$f \frac{L}{D} P_v$ psi	4 Elbows psi	TOTAL PRES- SURE DROP psi	GPM PER PASS
.15	.0365	3.59	16.5	1.73		12.4	7.5	22	2.67
.4	.0400	3.88	18.1	2.08		16.1	9.0	27	2.92
.857	.0464	4.34	21.0	2.80		24.3	12.1	40	3.39
1.4	.0525	5.05	23.8	3.59		36.3	15.5	49	3.62
3	.0441	5.09	20.0	2.53		25.8	10.9	40	3.22
4	.0417	5.21	18.9	2.26		23.5	9.8	36	3.06
5	.0383	5.33	17.3	1.91		20.4	8.3	31	2.80
6	.0350	5.72	15.9	1.59		18.2	6.9	27	2.56
6.4	.0265	5.70	12.0	.91		10.4	3.9	16	1.94
6.95	.0178	5.88	8.1	.41		4.8	1.8	8	1.30

Table 3.4-13 indicates channel heat transfer, water boundary layer ΔT , boiling suppression pressure and minimum frame coolant inlet pressures for a 600 m³/hour flow.

TABLE 3.4-13

CHANNEL WATER BOUNDARY LAYER ΔT , PLUS BOILING
SUPPRESSION AND INLET PRESSURES AT 600 m³/HR

FRAME STATION m	R_e	h Btu/hr ft ² °F	ΔT BOUNDARY LAYER °F		BOILING SUPPRES. TEMP. °F	BOILING SUPPRES. PRESS. psig	FRAME INLET PRESSURE psig, min.
			ELECTRODE	SLANTED			
.15	97757	5624	204	164	416	279	296
.4	106400	6018	194	154	406	250	271
.857	124100	6808	205	133	417	284	315
1.4	132300	7165	218	104	430	328	366
3	118000	6534	206	99	418	290	321
4	111550	6250	203	92	415	277	305
5	102460	5839	204	83	416	279	303
6	93665	5435	168	79	380	180	201
6.4	70930	4351	149	78	361	141	153
6.95	47590	3162	104	87	316	70	76

Table 3.4-14 indicates channel heat transfer, water boundary layer ΔT , boiling suppression pressure and minimum frame coolant inlet pressure for a 680 m³/hour flow.

TABLE 3.4-14

CHANNEL WATER BOUNDARY LAYER ΔT , PLUS BOILING
SUPPRESSION AND INLET PRESSURES AT 680 m³/HR.

FRAME STATION	R_e	ΔT BOUNDARY LAYER $^{\circ}F$			BOILING SUPPRES. TEMP., $^{\circ}F$	BOILING SUPPRES. PRESS. psig	FRAME INLET PRESSURE psig, min.
		h Btu/hr ft ² $^{\circ}F$	ELECTRODE	SLANTED			
.15	110791	6216	209	168	421	297	319
.4	120590	6652	199	158	411	265	292
.857	140650	7525	210	136	422	299	339
1.4	149940	7920	224	107	436	350	399
3	133750	7222	211	102	423	312	352
4	126400	6908	208	94	420	295	331
5	116120	6454	209	85	421	297	328
6	106153	6007	172	81	384	191	218
6.4	80390	4809	153	80	365	148	164
6.95	53940	3495	107	89	319	73	81

Table 3.4-15 indicates channel heat transfer electrode wall ΔT , including the fouling factor and ΔT for the inside wall, copper wall and the gas side wall at 600 m³/hour flow rate.

TABLE 3.4-15

CHANNEL HEAT TRANSFER ELECTRODE WALL ΔT AT 600 m³/HOUR

FRAME STATION m	ΔT , °F FOULING LAYER .0002	T, °F INSIDE WALL	ΔT , °F COPPER WALL .125"	T, °F GAS SIDE WALL
.15	229	645	49	694
.4	232	638	49	687
.857	277	694	59	753
1.4	310	740	66	806
3	266	684	57	741
4	251	666	53	719
5	236	652	50	702
6	181	561	38	599
6.4	129	490	27	517
6.95	66	382	14	396

Table 3.4-16 indicates channel heat transfer electrode wall ΔT , including the fouling factor and ΔT for the inside wall, copper wall, and the gas side wall at 680 m³/hour flow rate.

TABLE 3.4-16

CHANNEL HEAT TRANSFER ELECTRODE WALL ΔT at 680 m³/HOUR

FRAME STATION m	ΔT , °F FOULING LAYER	T, °F INSIDE WALL	ΔT , °F COPPER WALL	T, °F GAS SIDE WALL
	.0002		.125"	
.15	235	656	56	712
.4	238	649	56	705
.857	284	706	67	773
1.4	318	754	75	829
3	273	695	65	760
4	257	677	60	737
5	242	663	57	720
6	186	570	43	613
6.4	132	497	31	528
6.95	68	387	16	403

3.4.7.3 Before considering the specifics of diffuser cooling, refer to Fig. 3-19 to obtain a clear picture of diffuser cooling water passage configuration. Note that the diffuser water passages are axial to the gas flow, where the coolant passages of the nozzle and channel are radial with respect to gas flow.

Fig. 3-19. Diffuser Water Passage Configuration.

Figure 3-20 is a graphic illustration of heat transfer across the diffuser cooling section from 0.00 meters to 1.74 meters. The graph was derived from the tables discussed below.

Fig. 3-20. Heat Transfer Across Diffuser Cooling Section

Table 3.4-17 indicates the physical data for the diffuser upon which all diffuser cooling water calculations are based.

TABLE 3.4-17
DIFFUSER PHYSICAL DATA

STATION m	VERTICAL WALL INCH	HORIZ. WALL INCH	GAS FLOW AREA cm ²	FLOW AREA WATER INCH ²
0	24.4	46.1	7254	25.1
.25	25.3	48.0	7838	26.1
.50	26.2	49.9	8445	27.1
.75	27.1	51.9	9074	28.1
1.00	28.0	53.7	9719	29.1
1.25	28.9	55.7	10393	30.1
1.50	29.8	57.6	11090	31.1
1.74	30.7	59.4	11778	32.1

Table 3.4-18 indicates heat transfer across selected diffuser stations. The stations starting with zero were selected to give rates at 0.25 meter increments, along the length of the diffuser. The heat transfer is given for both the 600 m³/hour flow and the 680 m³/hour flow.

TABLE 3.4-18
HEAT TRANSFER ACROSS DIFFUSER

STATION m	600 m ³ /Hour		680 m ³ /Hour	
	$\dot{q}$ Watts/cm ²	Q, KW FOR 1 cm DIFFUSER LENGTH	$\dot{q}$ Watts/cm ²	Q, KW FOR 1 cm DIFFUSER LENGTH
0	75	26.85	85	30.43
.25	69.4	25.844	78.7	29.29
.50	64.4	24.91	73	28.23
.75	60	24.072	68	27.28
1.00	56	23.262	63.5	26.36
1.25	52.3	22.478	59.3	25.48
1.50	49.1	21.81	55.6	24.72
1.74	46.2	21.16	52.4	23.98
	190.386 KW for 8 cm		215.77 KW for 8 cm	

Tables 3.4-19 and 3.4-20 indicate water flow velocity and pressure drop for the 600 m³/hour cooling water flow rate and 680 m³/hour cooling water flow rate, respectively.

TABLE 3.4-19

DIFFUSER FLOW VELOCITY AND PRESSURE DROP AT 600 m³/HOUR

STATION m	V Ft/Sec	$\frac{\rho V^2}{2g}$ psi = P _v	$f \frac{L}{D_H} P_v$ psi	2 ELBOWS psi	TOTAL PRESS. DROP ΔP, psi
0	3.55	.08	.478	.15	1
.25	3.41				1
.50	3.28				1
.75	3.18				1
1.00	3.06	v e r y s m a l l v a l u e s			1
1.25	2.96				1
1.50	2.86				1
1.74	2.77				1

TABLE 3.4-20

DIFFUSER FLOW VELOCITY AND PRESSURE DROP AT 680 m³/HOUR

STATION m	V Ft/Sec	$\frac{\rho V^2}{2g}$ psi = P _v	$f \frac{L}{D_H} P_v$ psi	2 ELBOWS psi	TOTAL PRESS. DROP, ΔP, psi
0	4.02	.102	.612	.19	2
.25	3.86				2
.50	3.72				2
.75	3.60				2
1.00	3.47				2
1.25	3.35				2
1.50	3.24				2
1.74	3.14				2

Tables 3.4-21 and 3.4-22 indicate boiling suppression pressure and diffuser coolant water requirement for flows of 600 m³/hour and 680 m³/hour, respectively.

TABLE 3.4-21

COOLING WATER BOILING SUPPRESSION PRESSURE
AT 600 m³/HOUR FLOW

STATION m	R _e	$\frac{h}{ft^2}$ Btu/hr °F	ΔT , °F BOUND- ARY LAYER H ₂ O	T, °F BULK WATER	BOILING SUPP. TEMP. T, °F	PRESS. psig	TOTAL INLET PRESSURE psig
0	39063	1642	153	104	257	19	
.25	37523	1590	146	121	267	25	
.50	36092	1541	140	138	278	33	
.75	34991	1503	134	154	288	41	
1.00	33671	1458	128	169	297	49	
1.25	32570	1420	123	184	307	59	
1.50	31470	1381	119	198	317	71	
1.74	30480	1346	115	212	327	84	85

TABLE 3.4-22

COOLING WATER BOILING SUPPRESSION PRESSURE
AT 680 m³/HOUR FLOW

0	44271	1815	173	104	277	32	
.25	38474	1757	150	121	271	28	
.50	37007	1703	144	138	282	36	
.75	35878	1661	137	154	291	42	
1.00	34525	1612	131	169	300	52	
1.25	33396	1570	126	184	312	65	
1.50	32268	1526	122	198	320	75	
1.74	31253	1488	118	212	330	88	90

Tables 3.4-23 and 3.4-24 indicate diffuser heat wall ΔT , including the fouling factor and ΔT for the copper wall and the inside and gas walls for flow rates of 600 m³/hour and 680 m³/hour, respectively.

TABLE 3.4-23

DIFFUSER HEAT TRANSFER WALL ΔT AT 600 m³/HOUR FLOW

STATION m	ΔT , °F FOULING .0002	T, °F INSIDE WALL	ΔT , °F WALL .104" COPPER	T, °F OUTSIDE WALL
0	50	307	10	317
.25	46	313	9	322
.50	43	321	8	329
.75	40	328	7.7	336
1.00	37	334	7.2	341
1.25	35	342	6.7	349
1.50	33	350	6.3	356
1.74	31	358	5.9	364

TABLE 3.4-24

DIFFUSER HEAT TRANSFER WALL ΔT AT 680 m³/HOUR FLOW

0	57	334	12.4	347
.25	53	324	11.5	336
.50	49	331	10.6	342
.75	45.5	336.5	10	347
1.00	42.5	342.5	9.2	352
1.25	40	352	8.6	361
1.50	37	357	8.1	365
1.74	35	365	7.6	373

Figures 3-21 and 3-22 depict a summary of cooling system pertinent data as it applies to the channel system. It should be noted that the total heat transfer requirement for each major component, i. e., nozzle, channel and diffuser are shown. Also total cooling water flow in gallons per minute is shown for each major component. Figure 3-21 indicates the values for a 600 m³/hour flow rate and Fig. 3-22 indicates the values for a 680 m³/hour flow rate.

3.5 Structural Analysis

3.5.1 General Information. Analyses were conducted of factors which cause stress and deflection in the channel. The analyses were conducted for a pressure vessel design, including the nozzle and the diffuser. Before entering into any discussion of the formulae used in these analyses however, it is appropriate to briefly review the factors which cause stress and deflections. They are:

- A. Gas static pressure
- B. Thermal stresses
- C. Jet thrust
- D. Cooling water pressure stresses
- E. Gasket sealing and bolting forces
- F. Frame support forces
- G. Dead weight forces
- H. Forces applied by Soviet interfaces.

Each of the above factors is discussed in more detail in Paragraphs 3.5.1.1 through 3.5.1.7 below.

3.5.1.1 The rectangular channel, including the nozzle and diffuser, is exposed to internal gas pressures ranging from a positive 14.7 psig to a negative 8 psig (+14.7 psig to -8 psig). Considering these pressures, the channel must be designed and treated as a pressure vessel. Construction methods and wall thicknesses selected must be adequate to avoid either dangerous stress levels or intolerable wall deflections under both positive pressure and vacuum conditions.

3.5.1.2 Inasmuch as the gases flowing through the channel are in the 4000°F temperature range, heat loss to the channel wall cannot be avoided. To protect the channel structure, cooling water is circulated through the inner wall which is exposed to the gases. This inner wall, sandwiched between the cooling water and the high temperature gases will experience a high heat flow and therefore will have a temperature gradient. Due to thermal expansion, the hotter layers of the

FCV = FLOW CONTROL VALVE
 PCV = PRESSURE CONTROL VALVE
 P = PRESSURE TAP
 T = THERMOCOUPLE

WATER DISTRIBUTION
 AT 600 M³/HR

FCV : FLOW CONTROL VALVE
 PCV : PRESSURE CONTROL VALVE
 P : PRESSURE TAP
 T : THERMOCOUPLE

WATER DISTRIBUTION
AT 680 M³/HR.

wall will tend to expand more than the cooler layers. The net result of this uneven expansion is that a flat non-rigid cooling wall will curve into a spherical-shaped surface. A rigid flat wall can only remain flat if the hot layers are compressed and the cool layers are put in tension with the compression and tension forces balancing each other. Due to the high temperature gradient the thermal stresses would be very high resulting in great bowing-out of non-rigid components. Heat flowing into a rigid cooling water tube, for example, will cause thermal stresses because it is rigid and cannot assume another radius of curvature in one direction. Also, due to the rigidity growth in a linear direction is limited causing more thermal stress. The above discussion assumes uniform heat transfer through the wall.

3.5.1.3 The high exit velocity of the gases exerts a large compression force on the whole channel. The structure must be designed to withstand this additional compressive stress. Flanges perpendicular to the gas flow will experience this compression as an increased sealing force over and above that imparted by the initial bolt sealing force, a plus factor. The frames of the channel however, which are angled with respect to gas flow, will experience a shear force. This shear force indicates that dowel pins, or some other equivalent fastening technique, must be employed to prevent a sliding motion between the angled frames.

3.5.1.4 Cooling water pressure stresses can only be established after the friction drop and boiling suppression pressure requirements have been determined. The determination of these values was discussed in Paragraph 3.4 above. Once these values are known, the stress deflections on the cooling water passages can be calculated if the flow passage shape is known.

A round passage offers the lowest stress values. A rectangular passage will have much higher stresses due to bending moments, but it offers the advantage of a higher flow rate in the same amount of space. Stresses on a rectangular cooling water passage are calculated similarly to calculations for any other rectangular channel except that the pressure will be uniform on all sides.

The diffuser cooling water passage has a stiff outside wall which is treated as an edge supported plate with uniform pressure throughout. The heat transfer wall however, is a thin membrane that will be deflected into a curvature by hydraulic pressure during the fabrication process. This curvature assumes the characteristics of a portion of a pipe wall with tension forces only. These tension forces will cause some additional curvature, however, the tension forces are well below the yield point under normal operating water pressure conditions. This construction has the advantage of thermal expansion take-up in one direction by the additional bow-out of the membrane. The thermal stresses in the direction perpendicular to this are compensated for by the expansion joints in the diffuser outer wall.

3.5.1.5 Stresses and deflections caused by gasket sealing and bolting forces may be minimized if rubber can be utilized as the sealing material. Use of rubber sealing material will also enable the use of smaller bolts. If suitable sealing material of rubber is unavailable and stiffer gasketing material is utilized, larger bolts will be required and larger stresses and deflections will result.

3.5.1.6 Local stresses and deflections caused by the rolling elements used to install the channel in the HPDF, and possibly for other assembly and handling operations, must be considered. These forces and deflections will be small in comparison with other stresses and deflections that the channel will be subjected to.

3.5.1.7 The spacing between the rolling elements used to install the channel in the HPDF, and possibly other assembly and handling operations, must be carefully analyzed to minimize dead weight bending stresses and deflection in the channel.

Now that all of the factors involved in the overall channel design have been discussed, Paragraphs 3.5.2 through 3.5.4 will present formulae and tables used to assure that stress and deflection forces will not be excessive. The results of analyses for each major component will be presented on tables for that component starting with the nozzle.

3.5.2 Nozzle Design Analysis. The nozzle section of the channel system was designed to withstand all pressure and thermal stresses and deflections that it is expected to encounter. Stress in the nozzle is caused by the following:

- A. Water pressure in the cooling passages.
- B. Internal gas pressure, as the nozzle is a pressure vessel.
- C. Thermal stresses in the inner wall due to a temperature gradient across the wall.
- D. Thermal stresses due to the temperature differential between the cooled wall and the surrounding frame.

The formulae and tables discussed in Paragraph 3.5.2.1 will indicate pressure stress determination, and the formulae and tables of Paragraph 3.5.2.2 will indicate thermal stress determination.

3.5.2.1 Pressure stress and deflections of the nozzle frames were calculated for each frame. Formula used and calculations of water pressure stress and deflections are indicated below by the sample calculations for frame number 8:

Frame 8 has the highest value $B(=1.417")$ and the highest pressure $w(262 \text{ psig})$.

Stress and deflection case:

$w - 262 \text{ lbs/inch } \ell = 1.417"$
 Max. moment = $M = 9/128 w \ell^2 = 37 \text{ in lbs.}$

Max. bending stress:

$$S_b = \frac{M \times 6}{.25^2} = 3551 \text{ psi.}$$

Tensile stress S_1 in all three $1/8"$ walls:

$$S_1 = \frac{262 \times 1.417 \times 2}{3 \times .125} = 1980 \text{ psi.}$$

Table 3.5-1 indicates the nozzle frame dimensions and the calculated pressure stresses and deflections for each.

TABLE 3.5-1

NOZZLE PRESSURE STRESSES AND DEFLECTIONS

FRAME	l_1 inch	l_2 inch	w psig	M_0 in lb.	M_1 in lb.	M_2 in lb.	corner center defl. $EI \times y_1$ inch	center $EI \times y_2$ inch
1	29.3	23.0	31.5	1873	1507	210	101293	- 9074
2	29.2	20.0	29.7	1655	1510	-170	104753	-20875
3	29.1	17.6	27.7	1487	1445	-414	101236	-22969
4	29.1	15.7	25.6	1358	1352	-569	95283	-21589
5	29.0	14.2	23.6	1241	1240	-646	86881	-18785
6	29.0	13.0	21.6	1139	1132	-683	79185	-16029
7	28.9	12.2	19.8	1042	1025	-674	71058	-13675
8	28.8	11.7	17	892	871	-601	59803	-11115

Table 3.5-2 indicates the pressure stress values for candidate construction materials.

TABLE 3.5-2

PRESSURE STRESS VALUES FOR CANDIDATE MATERIALS

FRAME	S_T = $\frac{h}{25,000}$ psi	$\frac{h}{\text{for max. } y = .125''}$ COPPER $E=17 \times 10^6$	$\frac{h}{\text{for max. } y = .125''}$ STEEL $E=30 \times 10^6$	ALUM. $E=10^7$
1	.670	.830	.687	.991
2	.630	.839	.694	1.001
3	.597	.830	.687	.991
4	.571	.813	.673	.970
5	.546	.789	.653	.942
6	.523	.765	.633	.913
7	.500	.738	.611	.881
8	.463	.696	.576	.831

3.5.2.2 Due to the high heat transfer rates through the nozzle walls, a decision was made to use silver bearing copper as the construction material for the nozzle. Silver bearing copper will tend to minimize the thermal stresses. Table 3.5-3 indicates the heat input to the nozzle walls for both the 600 m³/hour and 680 m³/hour cooling water flow rates.

TABLE 3.5-3
HEAT INPUT STRESS TO NOZZLE WALLS

FRAME	600 m ³ /hr. S _{TH} , psi	680 m ³ /hr. S _{TH} , psi
1	3665	4082
2	4165	4665
3	4748	5331
4	5331	5998
5	5914	6581
6	6414	7247
7	6914	7747
8	7247	8080

Table 3.5-4 indicates temperature distribution in the frames, and the resultant thermal stress.

TABLE 3.5-4

FRAME TEMPERATURE DISTRIBUTION AND RESULTANT
THERMAL STRESS

Temperature distribution in frame,
and resultant thermal stress.

600 m ³ /hour				680 m ³ /hour		
FRAME	T _s , °F	T, °F	S _{TH} , psi	T _s , °F	T, °F	S _{TH}
1	445	335	18326	460	339	20159
2	476	350	20992	493	355	22991
3	508	365	23824	525	370	25823
4	537	379	26322	558	385	28822
5	566	392	28984	588	398	31654
6	591	403	31320	617	411	34320
7	614	413	33486	641	421	36652
8	634	423	35142	662	432	38318

Thermal expansion effect of heating wall:

$$\Delta l = \alpha l \Delta T = 9.8 \times 10^{-6} \times 2 \times 220 = .0043 \text{ inch}$$

for frame 7 at 680 m³/hour with max. ΔT .

$$y = \frac{Pl^3}{3EI} = .0022$$

$$l = .25" \quad E = 17 \times 10^6 \quad I = \frac{.125^3}{12}$$

$$\therefore P = 1169 \text{ lbs.}$$

$$S_t = \frac{M \times 6}{h^2} = \frac{1169 \times .25 \times 6}{.125^2} = 112200 \text{ psi.}$$

This corner will yield to reach .0022" deflection.

Center baffle is stretched due to cooling wall curving.

$$R = \frac{t}{\alpha \Delta T} = \frac{.25}{9.8 \times 10^{-6} \times 220} = 116"$$

$$R = \frac{a^2 + h^2}{2h} \quad a = 1" \quad 116 = \frac{1 + h^2}{2h} \quad h^2 = 232h + 1 = 0$$

$$\therefore h = .00431" = \frac{Pl}{AE} = \frac{P \times .25}{.125 \times 17 \times 10^6}$$

$$\therefore S_t = \frac{17 \times 10^6}{.25} \times .00431 = 29308 \text{ psi} \quad P = 36638 \text{ lbs.}$$

This stress will not be reached because the force P (between 0 and 36638 lbs depending on arch stiffness) will prevent bowing out.

Stiffness of arch, or force P to cause .0022" deflection:

$$y_{\max} = \frac{Pl^3}{48EI}$$

$$.0022 = \frac{P \times 2^3 \times 12}{48 \times 17 \times 10^6 \times .25^3}$$

$$\therefore P = 292.2 \text{ lbs.}$$

Therefore the center pillar will only stretch approximately $\frac{.0022"}{60} = .000037"$ at P = 290 lbs, and $S_t = 5000 \text{ psi.}$

3.5.3 Channel Design Analysis. The channel section of the channel system was designed to withstand all pressure and thermal stresses and deflections that it is expected to encounter. Pressure calculations will be discussed first, followed by thermal stress calculations and all other stress and deflection calculations.

3.5.3.1 Gas static pressure stress and deflections were calculated for each frame. These calculations are based upon the formulae and procedures outlined below. The results of these analyses are reflected on Table 3.5-7. It should be noted that in order to calculate pressure stresses for a trapezoidal frame, it is first necessary to analyze stresses for a rectangular pressure vessel as follows.

A. Rectangular frames with 90° corners and with a uniform pressure.

Each side (1) and (2) are the summation of two stress and deflection cases:

Case I: Both ends fixed, uniform load

Case II: End supports, end couples.

The boundary conditions for each side is the fact that their end moments and end angular deflections must be equal.

Equations for side (1)

Case I End Moments: $\frac{w l_1^2}{12} = M_1$

Center Moment: $\frac{w l_1^2}{24} = M_{1C}$

Center Deflection: $y_1 = \frac{w l_1^4}{384 EI_1}$

Case II End Moments: ΔM_1

Center Deflection: $y_1 = \frac{\Delta M_1 l_1^2}{8 EI_1}$

End Angular Deflection: $\phi_1 = \frac{\Delta M_1 l_1}{2 EI_1}$

Side (1) Total End Moment $M_{01} = M_1 - \Delta M_1$

Total Center Deflection $y_1 = \frac{w l_1^4}{384 EI_1} + \frac{\Delta M_1 l_1^2}{8 EI_1}$

Center Moment: $M_{1C} = \frac{w l_1^2}{24} + \Delta M_1$

End Angular Deflection $\phi_1 = \frac{\Delta M_1 l_1}{2 EI_1}$

Similarly:

Side (2) Total End Moment $M_{02} = +M_2 + \Delta M_2$

Total Center Deflection $y_2 = \frac{w l_2^4}{384 EI_2} - \frac{\Delta M_2 l_2^2}{8 EI_2}$

Center Moment: $M_{2C} = \frac{w l_2^2}{24} - \Delta M_2$

End Angular Deflection $\phi_2 = + \frac{\Delta M_2 l_2}{2 EI_2}$

Boundary Conditions:

$$M_{01} = M_{02} = M_0 \quad \text{and} \quad \phi_1 = \phi_2$$

Calculate M_0 , frame corner moment.

$$\text{From } \phi_1 = \phi_2 \therefore \frac{\Delta M_1 \ell_1}{2 EI_1} = \frac{\Delta M_2 \ell_2}{2 EI_2} \therefore \frac{\Delta M_1}{\Delta M_2} = \frac{\ell_2 I_1}{\ell_1 I_2} \quad (1)$$

$$\left. \begin{aligned} \Delta M_1 &= M_1 - M_0 \\ \Delta M_2 &= M_0 - M_2 \end{aligned} \right\} \therefore \frac{\Delta M_1}{\Delta M_2} = \frac{M_1 - M_0}{M_0 - M_2} \quad (2)$$

$$\text{Combine (1) and (2):} \quad \frac{\ell_2 I_1}{\ell_1 I_2} = \frac{M_1 - M_0}{M_0 - M_2} = \frac{\frac{w \ell_1^2}{12} - M_0}{M_0 - \frac{w \ell_2^2}{12}}$$

$$\text{or } \frac{w \ell_1^3}{12 I_1} - M_0 \frac{\ell_1}{I_1} = M_0 \frac{\ell_2}{I_2} - \frac{w \ell_2^3}{I_2 12}$$

$$M_0 \left(\frac{\ell_1}{I_1} + \frac{\ell_2}{I_2} \right) = \frac{w}{12} \left(\frac{\ell_1^3}{I_1} + \frac{\ell_2^3}{I_2} \right)$$

$$M_0 = \frac{w}{12} \frac{\frac{\ell_1^3}{I_1} + \frac{\ell_2^3}{I_2}}{\frac{\ell_1}{I_1} + \frac{\ell_2}{I_2}}$$

, See Roark, 4th ed, p.116, (12)

For $I_1 = I_2$:

$$M_0 = \frac{w}{12} \frac{\ell_1^3 + \ell_2^3}{\ell_1 + \ell_2}$$

The derivation shown above does not show a calculation sequence required to calculate all moments of each typical beam. The proper sequential calculations required to recommend a safe material height for each structural member follows.

Beam (1)

Step 1: Corner Moment $M_O = \frac{w}{12} \frac{\frac{l_1^3}{I_1} + \frac{l_2^3}{I_2}}{\frac{l_1}{I_1} + \frac{l_2}{I_2}}$

Step 2: Center Moment $M_{1C} = \frac{w l_1^2}{8} - M_O$

Step 3: Center Deflection $y_{1C} = \frac{5}{384} \frac{w l_1^4}{EI_1} - \frac{M_O l_1^2}{8 EI_1}$

Beam (2)

Step 1: Corner Moment as above (Note only)

Center Moment $M_{2C} = \frac{w l_2^2}{8} - M_O$

Step 2: Center Deflection $y_{2C} = \frac{5 w l_2^4}{384 EI_2} - \frac{M_O l_2^2}{8 EI_2}$

Stresses:

For each moment, the h value for a bending stress limit can be found:

$$S = \frac{M \times 6}{h^2} \quad \text{or} \quad h = \sqrt{\frac{M \times 6}{S}}$$

The above calculations are entirely adequate for a true rectangular pressure vessel, however they must be supplemented with further formulae and calculations if the vessel is of trapezoidal shape, which the channel is. The formulae and steps for trapezoidal calculations follow.

B. Trapezoidal Frames with Nonuniform Pressure

The procedure to find the corner moments and the center deflections is similar to the rectangular; uniform pressure, derivation.

Sides (1) and (4) (Identical loading) are ruled by the summation of Case II and Case II, with Case III described below.

Case III:

$$\text{Case III} = \text{Case a} + \text{Case b}$$

Case a:

End Moments:

$$\frac{w_1 l^2}{12}$$

Center Moment:

$$\frac{w_1 l^2}{24}$$

Center Deflection:

$$y = \frac{w_1 l^4}{384 EI}$$

Case b:

End Moments:

$$M_A = \frac{w_2 l^2}{20} \quad M_B = \frac{w_2 l^2}{30}$$

Center Moment:

$$M_{\text{center}} = \frac{7 w_2 l^2}{240}$$

Center Deflection:

$$y = \frac{w_2 l^4}{768 EI_1}$$

Side (1) and (4) equations: Summation of Cases II (See 3.2.1) and Case III.

$$M_A = \frac{w_1 l^2}{12} + \frac{w_2 l^2}{20} - \Delta M_{A1} = l^2 \left(\frac{w_1}{12} + \frac{w_2}{20} \right) - \Delta M_{A1}$$

$$M_B = l^2 \left(\frac{w_1}{12} + \frac{w_2}{30} \right) - \Delta M_{B2}$$

$$\text{Center Moment: } M_{\text{center } 1} = \frac{w_1 l_1^2}{24} + w_2 l_1^2 \times \frac{7}{740} - \frac{\Delta M_{A1} + \Delta M_{B2}}{2}$$

$$\text{Angular Deflections: } \phi_1 = \Delta M_{A1} l_1 / 2 EI_1$$

$$\phi_2 = \Delta M_{B2} l_1 / 2 EI_2$$

$$\text{Center Deflection: } y_1 = \frac{w_1 l_1^4}{384 EI_1} + \frac{w_2 l_1^4}{768 EI_1} + \frac{\Delta M_{A1} + \Delta M_{B2}}{2} \frac{l_1}{8 EI}$$

Side (2) Equations:

End Moments:

$$M_B = M_C = \frac{w_1 l_2^2}{12} + \Delta M_{B3} = \frac{w_1 l_2^2}{12} + \Delta M_{C4}$$

Center Moment:

$$M_{\text{center } 2} = \frac{w_1 l_2^2}{24} - \Delta M_{B3}$$

Angular Deflection:

$$\phi_3 = \phi_4 = \Delta M_{B3} l_2 / 2 EI_2$$

Center Deflection:

$$y_2 = \frac{w_1 l_2^4}{384 EI_2} - \frac{\Delta M_{B3} l_2^2}{8 EI_2}$$

$$M_{\text{center } 3} = \frac{(w_2 + w_1) l_3^2}{24} - \Delta M_{A8}$$

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Center Deflection: $y_3 = \frac{(w_2 + w_1) \ell_3^4}{384 EI_3} - \frac{\Delta M_A \ell_3^2}{8 EI_3}$

Solving for M_A , M_B , ΔM_A and ΔM_B from boundary conditions:

$$\phi_1 = \phi_8 \quad (1)$$

$$\phi_2 = \phi_3 \quad (2)$$

$$(1) \quad \frac{\Delta M_{A1} \ell_1}{2 EI_1} = \frac{\Delta M_{A8} \ell_3}{2 EI_3} \quad \therefore \frac{\Delta M_{A1}}{\Delta M_{A8}} = \frac{\ell_3}{I_3} \times \frac{I_1}{\ell_1} \quad (3)$$

Also:

$$\Delta M_{A1} = \ell_1^2 \left(\frac{w_1}{12} + \frac{w_2}{20} \right) - M_A$$

$$\Delta M_{A8} = M_A - \frac{\ell_3^2}{12} (w_2 + w_1)$$

Combine (3), (4) and (5):

$$\frac{\ell_3 I_1}{\ell_1 I_3} = \frac{\ell_1^2 \left(\frac{w_1}{12} + \frac{w_2}{20} \right) - M_A}{M_A - \frac{\ell_3^2}{12} (w_2 + w_1)}$$

$$\frac{\ell_3}{I_3} M_A - \frac{\ell_3^3}{I_3} \frac{w_2 + w_1}{12} = \frac{\ell_1^3}{I_1} \left(\frac{w_1}{12} + \frac{w_2}{20} \right) - \frac{\ell_1}{I_1} M_A$$

$$M_A = \frac{\frac{\ell_1^3}{I_1} \left(\frac{w_1}{12} + \frac{w_2}{20} \right) + \frac{\ell_3^3}{I_3} \left(\frac{w_2 + w_1}{12} \right)}{\frac{\ell_1}{I_1} + \frac{\ell_3}{I_3}}$$

Similarly:

$$M_B = \frac{\frac{\ell_1^3}{I_1} \left(\frac{w_1}{12} + \frac{w_2}{30} \right) + \frac{\ell_2^3}{I_2} \frac{w_1}{12}}{\frac{\ell_1}{I_1} + \frac{\ell_2}{I_2}}$$

For $I_1 = I_2 = I_3$:

$$M_A = \frac{\ell_1^3 \left(\frac{w_1}{12} + \frac{w_2}{20} \right) \ell_3^3 \left(\frac{w_1 + w_2}{12} \right)}{\ell_1 + \ell_3}$$

$$M_B = \frac{\ell_1^3 \left(\frac{w_1}{12} + \frac{w_2}{30} \right) \ell_2^3 \left(\frac{w_1}{12} \right)}{\ell_1 + \ell_2}$$

The above derivation shown does not show a calculation sequence required to calculate all moments of each typical frame. The proper sequential calculations required to recommend a safe material height for each structural member follows:

Beam (1) (Identical to Beam (4)) ($I_1 = I_{II}$)

Step 1: Corner Moment

$$M_A = \frac{\ell_1^3 \left(\frac{w_1}{12} + \frac{w_2}{20} \right) + \ell_3^3 \left(\frac{w_1 + w_2}{12} \right)}{\ell_1 + \ell_3}$$

Step 2: Corner Moment

$$M_B = \frac{\ell_1^3 \left(\frac{w_1}{12} + \frac{w_2}{30} \right) + \ell_2^3 \left(\frac{w_1}{12} \right)}{\ell_1 + \ell_2}$$

Step 3: Corrective Moment:

$$\Delta M_{A1} = \ell_1^2 \left(\frac{w_1}{12} + \frac{w_2}{20} \right) - M_A$$

Step 4: Corrective Moment:

$$\Delta M_{B2} = \ell_1^2 \left(\frac{w_1}{12} + \frac{w_2}{30} \right) - M_B$$

Step 5: Average Corrective Moments:

$$\frac{\Delta M_{A1} + \Delta M_{B2}}{2} = \Delta M_1$$

Step 6: Center Moment:

$$M_{1C} = \frac{w_1 \ell_1^2}{24} + \frac{7w_2 \ell_1^2}{240} - \Delta M_1$$

Step 7: Center Deflection:

$$y_{1C} = \frac{w_1 \ell_1^4}{384 EI_1} + \frac{w_2 \ell_1^4}{768 EI_1} + \frac{\Delta M_1 \ell_1^2}{8 EI_1}$$

Beam (2)

Step 1: Corner Moment Identical to M_B (Note only)

Corrective Moment:
$$\Delta M_{B3} = \frac{\ell_1}{\ell_2} \times \Delta M_1 \text{ (see Step 5 above)}$$

Step 2: Center Moment:
$$M_{2C} = \frac{w_1 \ell_2^2}{24} - \Delta M_{B3}$$

Step 3: Center Deflection:
$$y_2 = \frac{w_1 \ell_2^4}{384 EI_2} - \frac{\Delta M_{B3} \ell_2^2}{8 EI_2}$$

Beam (3)

Step 1: Corner Moment Identical to M_A (Note only)

Corrective Moment:
$$\Delta M_{A8} = \frac{\ell_1}{\ell_3} \times \Delta M_1 \text{ (see Step 5 above)}$$

Step 2: Center Moment:
$$M_{3C} = \frac{(w_2 + w_1) \ell_3^2}{24} - \Delta M_{A8}$$

Step 3: Center Deflection:
$$y_{3C} = \frac{(w_2 + w_1) \ell_3^4}{384 EI_3} - \frac{\Delta M_{A8} \ell_3^2}{8 EI_3}$$

NOTE: Since the above moments are the maximum moments in their immediate vicinity, the minimum material height values at their locations may be derived by use of formula:

$$h = \sqrt{\frac{M \times 6}{5}} \text{ based on a safe stress 5 psi.}$$

The center deflection rules the design.

Figure 3-23 indicates a typical channel frame configuration with call outs of all parameters considered in the stress and deflection analyses.

Fig. 3-23. Typical Channel Frame

Table 3.5-5 indicates channel frame data at selected stations along the channel upon which stress and deflection calculations are based.

TABLE 3.5-5
CHANNEL FRAME BASIC DATA

STATION m	ℓ_1 inch	ℓ_2 inch	ℓ_3 inch	ϕ Degrees	$\ell_1 \sin \phi$ inch	w_1 psig	w_2 psig
.15	31.3	13.4	13.0	22.25	.301	12.11	.85
.4	33.3	13.8	13.2	29.63	.589	11.02	1.63
.857	37.9	14.7	13.7	40.60	.626	8.88	2.57
1.4	45.6	15.6	14.3	50.18	.889	7.84	2.46
3	44.3	17.2	16.4	43.55	.776	3.57	2.15
4	44.2	18.9	17.6	38.48	.699	.90	1.94
5	44.3	20.5	18.7	32.60	.607	-1.74	1.68
5.9	45.6	23.7	22.4	26.57	.516	-4.11	1.43
6.3	44.4	24.3	23.7	17.20	.334	-4.96	.92
6.95	46.1	24.4	24.4	0	0	-6.30	0

Table 3.5-6 indicates the calculated bending moments M and deflections Δ .

TABLE 3.5-6

BENDING MOMENTS "M" AND DEFLECTIONS "Δ"

STATION m	M_A INLB.	M_B INLB.	M at $\frac{\ell_1}{2}$ INLB.	M at $\frac{\ell_2}{2}$ INLB.	M at $\frac{\ell_3}{2}$ INLB.	Δ at $\frac{\ell_1}{2}$ x EI	Δ at $\frac{\ell_2}{2}$ x EI	Δ at $\frac{\ell_3}{2}$ x EI
.15	781.2	766	-768	492	509.4	60600	-12000	-11200
.4	835.6	804	-816.5	683.4	536.7	72800	-17300	-12700
.857	963.5	899	-923.7	654.4	698.4	106000	-18800	-18200
1.4	1271	1180	-1093	694.1	756.2	171000	-22300	-20500
3	614.4	546.3	-593.4	417.2	419.5	90500	-16200	-15200
4	381.6	317.2	-391.5	260.0	273.6	48800	-12600	-11300
5	-84.5	-138.5	81.4	-46.1	-83.1	-17700	3200	3650
5.9	-414.4	-468.8	415.3	-185.1	-241.6	-76000	16400	16900
6.3	-537.6	-573.6	583.4	-296.7	-334.8	-102000	27000	26800
6.95	-837.8	-837.8	835.8	-368.8	-368.8	-148000	34100	33300

The above calculations are based on a constant moment of inertia I for all spans, or for constant h values.

The dominating stresses are caused by the bending moments and the h value. Table 3.5-7 indicates the h value required to maintain a safe stress level in three candidate materials, i.e., steel, copper and aluminum.

It should be noted that only in the vertical frame members is there a change of sign occurring which indicates two locations of zero bending moment, therefore low stresses. These low stress locations are the ideal areas for cooling water inlet and outlet connections to be made if physical considerations will allow it. The ideal location for coolant connections, by calculation, would be 15% of the total members length measured from each corner.

Structural member deflections must not be greater than $1/8''$. The largest deflections are in structural member ℓ_1 , thus the values shown in Table 3.5-7 are calculated to prevent greater than $1/8''$ deflections in this worst case area.

TABLE 3.5-7

HEIGHT OF FRAMES REQUIRED FOR CHANNEL

STATION m	h for $S_t=25000$ psi	COPPER $E=17 \times 10^6$ h , inch	STEEL (S.S.) $E=30 \times 10^6$ h , inch	ALUM. $E=10^7$ h , inch
.15	.433"	.700	.579	.834
.4	.448"	.744	.615	.887
.857	.481"	.842	.697	1.005
1.4	.552"	.982	.818	1.179
3	.384"	.800	.662	.954
4	.303"	.651	.538	.776
5	.182"	.464	.384	.554
5.9	.335"	.755	.625	.901
6.3	.375"	.832	.497	.993
6.95	.448"	.942	.779	1.124

3.5.3.2 Channel thermal stress was calculated for each frame. These calculations were made for three different thermal conditions which can be distinguished for the channel. They are:

- A. Thermal stress in the heat input wall of the copper cooling water tubing.
- B. Thermal stress in the total cooling water tube without including attachment to the frame.
- C. Thermal stresses of the combined tube and frame.

Table 3.5-8 indicates the stresses caused by heat input to the electrode wall only, using cooling water flow rates of 600 m³/hour and 680 m³/hour, respectively.

TABLE 3.5-8
HEAT INPUT STRESSES IN ELECTRODE WALL

FRAME STATION m	Electrode Wall .125" Copper	
	600 m ³ /hr S _{TH} , psi	680 m ³ /hr S _{TH} , psi
.15	4082	4665
.4	4082	4665
.857	4915	5581
1.4	5498	6247
3	4748	5415
4	4415	4998
5	4165	4748
6	3166	3582
6.4	2249	2582
6.95	1166	1333

The calculations shown in Table 3.5-8 used in conjunction with the formulae and rationale shown below will indicate the stresses for the total cooling tube without the frame attached.

The temperature distribution in the tube wall is calculated using a "fin" model:

FIN, 0.25" THICK, .345 LONG INSULATED END, WATER BOTH SIDES.

T_s is the average heat input wall temperature. The temperature T_x is calculated with the formula:

$$\frac{T_x - T_\infty}{T_s - T_\infty} = \frac{e^{mx}}{1 + e^{2mL}} + \frac{e^{-mx}}{1 + e^{-2mL}}$$

where

T_∞ = water temperature (bulk)

$$m = \sqrt{\frac{2U}{kL(\text{ft})}}$$

$$\frac{1}{U} = .0002 + \frac{1}{h} \quad \text{for a fouling factor of .0002}$$

h = convective heat transfer coefficient

Utilizing the formulae and calculation rationale above, the results are reflected on Table 3.5-9. Note that Table 3.5-9 indicates values for both the 600 m³/hour and 680 m³/hour cooling water flow rates.

TABLE 3.5-9

FRAME STATION m	600 m ³ /hour			680 m ³ /hour		
	T _s °F	T °F	S _{th} psi	T _s °F	T °F	S _{th} psi
.15	670	516	12828	684	521	13578
.4	663	509	12828	677	513	13661
.857	724	542	15161	740	547	16077
1.4	773	571	16827	792	577	17940
3	713	537	14661	728	542	15494
4	693	527	13828	707	531	14661
5	677	520	13078	692	594	13994
6	580	458	10163	592	462	10829
6.4	504	415	7414	513	418	7914
6.95	389	342	3915	395	344	4248

The tube material will be silver bearing copper which was chosen for its elevated temperature strength. The selection of copper as the tube material was based upon its high heat transfer, low thermal stress characteristic, and the fact that thermal stresses dominate the design. Table 3.5-10 indicates that if other materials were chosen, the thermal stresses and heat input wall temperatures would be much higher.

TABLE 3.5-10

HEAT STRESS AND WALL TEMPERATURE COMPARISON
FOR CANDIDATE COOLING PASSAGE MATERIALS

	$T_s, ^\circ\text{F}$	$T, ^\circ\text{F}$	S_{TH}, psi
Silver Copper	773	567	16827
Aluminum	815	460	25027
Steel	1016	297	90594

Inasmuch as the cooling water passages are made an integral part of the frame by either brazing or welding, the temperature distribution in the cooling channel frame assembly and the attendant thermal stresses are calculated in much the same manner as the T calculations for the nozzle. Heat will transfer from the copper channel (with its high heat transfer efficiency) into the frame. The frame which is also cooled by the water will have a relatively low heat transfer to the surrounding air. Reference to Table 3.5-10 will indicate the poorer heat transfer values for aluminum and steel. These poorer heat transfer values plus the large mass of the frame will cause a differential of expansion between the hotter tube walls and the frame resulting in thermal stresses. The formulae and rationale utilized to determine these values is shown below.

In this simplified calculation, T_s is the average heat input wall temperature from previous tables, while T is assumed constant due to low heat loss by ambient air cooling.

From a heat balance: $Q_1 = Q_2 + Q_3$

where: $Q_1 = 226 \times \frac{.25}{.25} (T_s - T) = 226 T_s - 226 T$

$$Q_2 = 2 \times U \times \frac{.25}{12} \left(\frac{T_s + T}{2} - 212 \right) = .02083 UT_s + .02083 UT - 8.833 U$$

$$Q_3 = U \times \frac{.19}{12} (T - 212) = .01583 UT - 3.357 U$$

$$\frac{1}{U} = .0002 + \frac{1}{h}, \quad U = \text{overall heat transfer coefficient.}$$

Combining equations:

$$T = \frac{T_s (226 - .02083 U) + 11.19 U}{226 + .0366 U}$$

Thermal stress:

$$S_{TH} = \alpha E (T_s - T) = 16.6 (T_s - T)$$

(frame mass at T^0 will prevent expansion of thin walls.)

Q_1 and heat leak into the frame can be reduced by thinner side walls. This will increase the temperature differential $T_s - T$, and also the thermal stress S_{TH} in the frame wall as indicated in Fig. 3-24.

Fig. 3-24. Thermal Stress vs Frame Thickness

Assume a $U = 3000 \text{ Btu/hr ft}^2 \text{ } ^\circ\text{F}$ and $T_s = 700^\circ\text{F}$, with a side wall thickness t , varying as shown: $t = .125''$, $.093''$, $.062''$, $.031''$. Equations:

$$Q_1 = Q_2 + Q_3$$

$$Q_1 = 226 \times \frac{2t}{.25} (T_s - T) = 1.265 \times 10^6 t - 1808 t T$$

$$Q_2 = 125 \left(\frac{T_s + T}{2} - 212 \right) = 17250 + 62.5 T$$

$$Q_3 = 250 (.44 - 2t) (T - 212) = -500 t T + 106000t + 110 T - 23320$$

t	$.125''$	$.093''$	$.062''$	$.031''$
Q_1	$158125 - 226T$	$117645 - 168T$	$78430 - 112T$	$39215 - 56T$
Q_2	$17250 + 62.5T$	$17250 + 62.5T$	$17250 + 62.5T$	$17250 + 62.5T$
Q_3	$-10070 + 47.5T$	$-13462 + 63.5T$	$-16748 + 79T$	$-20034 + 94.5T$
$Q_2 + Q_3$	$-7180 + 110T$	$3788 + 126T$	$502 + 141.5T$	$-2784 + 157T$
$T, ^\circ\text{F}$	492	387	307	197
$S_{TH}, \text{ psi}$	34528	52146	65474	83800

The calculations relative to the heat transfer and thermal stresses for a combination of silver bearing copper cooling channel and silver bearing copper frames is indicated on Table 3.5-11.

TABLE 3.5-11
HEAT TRANSFER AND THERMAL STRESSES FOR CHANNEL
COOLING/FRAME COMBINATICN

FRAME STATION m	600 m ³ /hour			680 m ³ /hour		
	T _s , °F	T, °F	S _{TH} , psi	T _s , °F	T, °F	S _{TH} , psi
.15	670	446	37318	684	456	37985
.4	663	437	37652	677	438	39817
.857	724	459	44149	740	460	46648
1.4	773	480	48814	792	481	51813
3	713	457	42650	728	457	45149
4	693	450	40484	707	450	42816
5	677	447	38318	692	447	40817
6	580	401	29821	592	401	31821
6.4	504	371	22158	513	371	23657
6.95	389	316	12162	395	316	13161

3.5.3.3 Stress loading of the channel due to the jet thrust effect of the gases as they pass through the channel are discussed below. It has been calculated that this thrust will have a force of ten (10) tons, or 20,000 pounds. Additional design provisions to handle or reduce loads imposed by length component or in steam generator will be required here. This force acts as a compression force on the bolted and gasketed frames which tends to enhance the gas sealing capabilities of the channel system which is desirable. The undesirable aspect of this force is the shear force exerted on the slanted sections of the channel.

Calculations for jet thrust are:

$$\text{JET THRUST: } F = \frac{\dot{m}}{q} \Delta V$$

where: the jet thrust by the diffuser ΔV is 20,000 pounds, with minimal ΔV in the channel.

The result is that the channel has a 20,000 pound compression force applied.

Shear force on the slanted section is calculated as follows:

$$\text{Shear Force } F_S = 20,000 \cos \phi .$$

$$\text{For } x = 0: \phi = 40^\circ$$

$$F_S = 15321 \text{ lbs.}$$

$$\text{For } x = 204" \phi = 67^\circ$$

$$F_S = 7815 \text{ lbs.}$$

Thus, given a 1080 lbs shear force per 1/4-20 bolt, 14 bolts minimum are required to join two adjacent frames at $x = 0$, and 8 bolts are required at $x = 204"$.

Bolts can slide in their bolt holes under shear stress, therefore it is deemed desirable to supplement them with plastic dowel pins. This is proven by the following calculations which show bolt spacing without shear pins and with shear pins.

Bolt spacing without shear pins is calculated as follows:

x = 0 neutral axis length: $(30.5 + 14.8) \times 2 = 90.6''$ for 71 bolts;
 spacing required: $1.276''$.

x = 204 neutral axis length: $(43.5 + 24.25) \times 2 = 135.5''$ for 36 bolts;
 spacing required: $3.764''$.

Utilizing $1/4''$ fiberglass dowels to make the shear force, the dowel spacing becomes:

x = 0 spacing: $\frac{90.6}{32} = 2.83''$

x = 204 spacing: $\frac{135.5}{16} = 8.469''$

With fiberglass dowel pins of $1/4''$ diameter (which need no insulation) taking the shear load it is practical to use greater bolt spacing. The design accommodates this type of construction.

Theoretically, with dowel pins taking all the shear load, no bolts would be required for the shear stress in the channel. Practically speaking, however, $1/4$ -20 bolts are still required for compressing the gasket under "no load" conditions and also to hold the channel together. Since the bolts have an assumed friction factor of 0.1, they will also resist shear forces. A combination of bolts and plastic dowel pins therefore assures that shear stress in the channel will be minimized.

3.5.3.4 Channel cooling water pressure stresses and deflections were calculated utilizing the formulae and approach shown below:

Calculate for 1000 psig, and observe proportionality rule for other pressures.

Corner Moment:

$$M_o = \frac{1000}{12} \frac{.25^3 + .19^3}{.25 + .19} = 4.258 \text{ in lbs.}$$

Center Moment:

$$\frac{1000 \times .25^2}{8} - 4.258 = 3.555 \text{ in lbs.}$$

$$I = \frac{.125^3}{12} = 1.6276 \times 10^{-4} \text{ in}^4 \quad S = \frac{4.258 \times .0625}{1.6276 \times 10^{-4}} = 1635 \text{ psia}$$

Calculate deflection max. for copper

$$y = \frac{5}{384} \frac{1000 \times .25^4}{17 \times 10^6 \times 1.6276 \times 10^{-4}} - \frac{4.258 \times .25^2}{8 \times 17 \times 10^6 \times 1.6276 \times 10^{-4}}$$

$$= 6.36 \times 10^{-6} \text{ in.}$$

As may be seen, the stresses and deflections caused by cooling water pressure are so low that they are considered to be negligible.

3.5.3.5 Gasket sealing and bolting forces are determined by the type of gasket used and the gasket relaxation allowed. Bolt spacing is also determined by the type of gasket used and the gasket relaxation allowed. Any bolting spacing selected will have a large safety factor when the channel is operated due to the jet thrust compression force discussed in Paragraph 3.5.3.3 above.

For purposes of this discussion, "O" ring gasket sealing will be addressed.

"O" Ring Seal

As may be seen on the "O" ring sealing sketch, the interface area between plates will have a space which will be filled by the "O" ring, an outer gasket of flat material, and an inner area filled with a refractory material.

"O" ring seals for this type of application are available in only two standard sizes:

1/16" NOM. (.070) with .051" to .053" = L
 3/32" NOM. (.173) with .081" to .083" = L

Size L for the "O" ring will be determined by the thickness of the gasket utilized for the outer seal. Further, the "O" ring must be placed as near to the bolting space as possible.

Bolt spacing is determined by the gasket relaxation allowed when the channel is not under jet thrust compression load. This gasket relaxation is assumed to be .005" for purposes of designing the bolt hole spacing. Bolt spacing for gas sealing purposes is calculated by the following procedure:

The diagrams show a bolted joint with a gasket. The gasket is represented as a circle with a diameter of .041. The distance from the center of the gasket to the center of the bolt hole is .062. The distance from the center of the gasket to the center of the bolt hole is .103. The distance from the center of the gasket to the center of the bolt hole is .103. The distance from the center of the gasket to the center of the bolt hole is .103.

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$$y_{\min} = .103 - .089 = .014''$$

$$y_{\max} = .041 - .014 = .027''$$

$$E = \frac{G}{A} \times 100\% = \frac{.041}{.103} \times 100\% = 39.806\%$$

$$E = 8.93 F^{.4233} \quad F = 34.15 \text{ lbs/inch}$$

$$y_{\min} = \frac{wl^4}{384 \times E \times I} \quad I = \frac{1.5 \times .5^3}{12} = .0156 \text{ in}^4$$

$$l^4 = \frac{384 \times E \times .0156 \times y_{\min}}{34.15} = 4.744 \times 10^{-3} \times E$$

for steel: $l = 19.42''$ for copper: $13.2''$

Limit for 1/4-20 bolt: Assume Grade 5 with 2700 lbs proof load at 80%: 2160 lbs allowed:

$$l = \frac{2160}{34.15} = 70''.$$

3.5.3.6 Frame support stress and deflections are a function of the stiffness of the overall channel and the distance between mounting points. The formulae used and the rationale for determining stress and deflections are given below:

Due to use of 1/16" fiberglass gaskets between metal frames, assume an E of 1,800,000 psi (fiberglass) for the column.

$\alpha = 0$

$t = 1 \frac{1}{2}$ " with cooling water canal deducted.

$$I = [31.74 \times 16.3^3 - 28.74 \times 13.3^3] \times 1/12 = 5820 \text{ in}^4$$

$$wt = 1.75'' \times 1'' \times (15 + 30.5) \times 2 \times .3 = 48 \text{ lbs/inch}$$

$\alpha = 204^\circ$

$$I = \frac{45 \times 25.75^3 - 42 \times 22.75^3}{12} = 22816 \text{ in}^4$$

$$wt = 1.75 \times 1'' \times (24.5 + 43.75) \times 2 \times .3 = 72 \text{ lbs/inch}$$

Calculate with $I = 5820 \text{ in}^4$, $wt = 48$ for first order of magnitude stress and deflection investigation.

l is distance between supports. Weight estimate: 48 lbs/in.

$$M_{\max} = \frac{wl^2}{12} = 4l^2$$

$$S_{al} = \frac{10 \times 2160}{1.5 \times 30.5} = 472 \text{ psi, based on 10 } 1/4\text{-20 bolts at bottom wall.}$$

$$S_{al} = \frac{M \times e}{I} = \frac{4l^2 \times 16.3 \times 1/2}{22816} = 472$$

$$l^2 = \frac{472 \times 22816 \times 2}{4 \times 16.3} = 330435 \quad l = 575''$$

Strengthwise l can be very long.

Deflection:

$$y_{\max} = \frac{wl^4}{384 EI} = \frac{4l^4}{384 \times 1,800,000 \times 22816} = .062''$$

$$l^4 = 384 \times 1,800,000 \times 22816 \times .002 \times 1/4 = 2.444 \times 10''$$

$$l = 703''$$

When the channel is mounted in the Soviet magnet, the longest unsupported span will be approximately fifty (50) inches. Since this span is very short when compared to the above, deflections due to its own weight will be minimized.

For mounting in the AEDC magnet, the channel will be supported by twenty-four (24) Thompson Roundway bearings. The load applied to these bearings by the channel weight varies between 380 to 480 pounds depending upon the axial location of the bearings. Since the load capacity of a single Thompson Roundway bearing is 3,000 pounds and a dual Thompson Roundway bearing load capacity is 4,300 pounds, an ample margin of safety and a minimum of deflection can be expected.

3.5.3.7 Dead weight stresses and deflections when the channel is mounted in either the Soviet magnet or the AEDC magnet will be the same as those discussed in Paragraph 3.5.3.6 above, which indicated that they would be minimal.

During handling at the AEDC facility, dead weight handling stresses and deflections will be minimal as the channel system will be supported by the Thompson Roundway bearings and the assembly handling fixture.

During handling at the Soviet facility, the dead weight stresses and deflections will also be minimal as the channel system will also be supported by the Thompson Roundway bearings and the assembly handling fixture until ready for

lifting into the magnet. The lifting beam attached to the overhead crane and channel assembly for this purpose will provide adequate support points to assure that no more stress is applied during lifting than is applied for any other handling operation.

3.5.4 Diffuser Design Analysis. Diffuser design analysis consisted of analyzing stress and deflections caused by the following conditions:

- A. Cooling water pressure stresses.
- B. The fact that the diffuser is a vacuum chamber operated at approximately 8 psi below atmospheric pressure.
- C. Thermal stresses in the inner wall due to a temperature gradient.
- D. Thermal stresses in the double wall due to a water boundary layer ΔT of substantial magnitude.
- E. Compression stresses due to the jet thrust.

The design philosophy for the diffuser is to reduce the highest stress values, which are caused by the thermal forces, through the use of diffuser expansion joints. This philosophy is explained below to clarify the calculations and tables which follow.

A-A Operating Conditions

Water pressure and thermal gradient causes the inner wall to act as an expansion joint in one direction only, with the deflection in the direction shown in the accompanying sketch.

In the outer wall, the pressure vessel expansion joints take up thermal expansion as shown in the sketch below.

B-B Room Temperature

B-B Operating Conditions

The formulae and tables used to determine these stresses and deflections are discussed in Paragraphs 3.5.4.1 and 3.5.4.2, where 3.5.4.1 discusses pressure stresses and 3.5.4.2 discusses thermal stresses.

3.5.4.1 Diffuser pressure stress analyses were based on the formulae and rationale shown below. It should again be noted that this rectangular pressure vessel operates under vacuum conditions of approximately minus eight (-8) psi.

Corner moment for equal moment of inertias of both spans l_1 and l_2 M_0 is:

$$M_0 = \frac{w}{12} \frac{l_1^3 + l_2^3}{l_1 + l_2}$$

Center moment M_1 of span ℓ_1 :

$$M_1 = \frac{w \ell_1^2}{8} - M_o$$

Center moment M_2 of span ℓ_2 :

$$M_2 = \frac{w \ell_2^2}{8} - M_o$$

Center deflection y_1 of span ℓ_1 :

$$y_1 = \frac{5}{384} \frac{w \ell_1^4}{EI} - \frac{M_o \ell_1^2}{8 EI}$$

Center deflection y_2 of span ℓ_2 :

$$y_2 = \frac{5}{384} \frac{w \ell_2^4}{EI} - \frac{M_o \ell_2^2}{8 EI}$$

$$w = 8 \times \text{pitch} = 50 \text{ lbs/inch}$$

M_o , M_1 , M_2 , y_1 and y_2 are calculated for 8 stations along the diffuser, as shown in Table 3.5-12.

Max. Bending Moment Stress
Expansion Joint Reinforcing Rib

TABLE 3.5-12

DIFFUSER BENDING MOMENTS AND DEFLECTIONS

STATION m	ℓ_1 inch	ℓ_2 inch	w, lbs/in. 8#x6.25"	Center Corner of Span			Deflection at Center of span	
				M_o in lb	M_1 in lb	M_2 in lb	$EI \times y_1$	$EI \times y_2$
0	46.1	24.4	50	6649	6634	-2928	1.17×10^6	$-.264 \times 10^6$
.25	48.0	25.3	50	7207	7193	-3206	1.38	-.310
.50	49.9	26.2	50	7788	7775	-3498	1.61	-.361
.75	51.9	27.1	50	8423	8412	-3833	1.89	-.422
1.00	53.7	28.0	50	9017	9006	-4117	2.16	-.483
1.25	55.7	28.9	50	9700	9691	-4480	2.50	-.558
1.50	57.6	29.8	50	10372	10364	-4822	2.86	-.638
1.74	59.4	30.7	50	11030	11022	-5139	3.24	-.721

Upon completion of calculations of corner bending moments and deflections at the center of the span, the moments of inertia for the expansion joint and the reinforcing rib are calculated using the formulae and rationale shown below.

Moment of inertia of the expansion joint.

$$A_1 = 1.562 \text{ in}^2$$

$$A_2 = .613 \text{ in}^2$$

$$y_1 = .316 \text{ in}$$

$$y_2 = .804 \text{ in}$$

$$I_1 = .0081 \text{ in}^4$$

$$I_2 = .1430 \text{ in}^4$$

$$C_1 = \frac{4}{3\pi} \frac{R^2 + Rr + r^2}{R + r} = .995 \quad C_2 = .63''$$

$$\text{Combined inertia:} \quad I_1 = .0081 + .316^2 \times 1.562 = .1641$$

$$I_2 = .1430 + .804^2 \times .613 = .7894$$

$$l'_1 = y_1 + .125 = .441 \text{ in.} \quad I_{\text{total}} = .9535 \text{ in}^4$$

$$l'_2 = y_2 + C_2 = 1.434 \text{ in.}$$

Moment of inertia of the reinforcing rib.

$$A_1 = 1.562 \text{ in}^2$$

$$A_2 = 2.5 \text{ in}^2$$

$$y_1 = .462 \text{ in}$$

$$y_2 = .288 \text{ in}$$

$$l_1 = .587 \text{ in}$$

$$l_2 = .913 \text{ in}$$

$$I_1 = .0081 \text{ in}^4$$

$$I_2 = .3255 \text{ in}^4$$

Combined inertia:

$$\begin{aligned}
 I_1 &= .0081 + .462^2 \times 1.562 = .3415 \text{ in}^4 \\
 I_2 &= .3255 + .288^2 \times 2.5 = .5299 \text{ in}^4 \\
 I_{\text{total}} &= .8714 \text{ in}^4
 \end{aligned}$$

The maximum bending stress at each station is calculated using:

$$s = \frac{M \times \ell'_2}{I}$$

where M is shown on Table 3.5-12 and ℓ'_2 and I are shown in the calculations above.

The stresses are shown in Table 3.5-13 below.

TABLE 3.5-13
MAXIMUM BENDING MOMENT STRESS

STATION m	Maximum Bending Moment Stress, psi	
	Exp. Joint	Reinf. Rib
0	10,000	6,966
.25	10,839	7,551
.50	11,713	8,160
.75	12,668	8,825
1.00	13,561	9,447
1.25	14,588	10,163
1.50	15,599	10,867
1.74	16,588	11,557

The maximum deflections which will occur at selected stations along the diffuser are calculated using:

$$y_1 = \frac{5}{384} \frac{wl_1^4}{EI} - \frac{M_0 l_1^2}{8 EI}$$

The maximum deflection of the expansion joint and reinforcing rib at selected stations along the diffuser is shown in Table 3.5-14, below.

TABLE 3.5-14
DIFFUSER MAXIMUM DEFLECTIONS

STATION m	Deflection y_1 , inch for silver copper, $E = 17 \times 10^6$	
	Exp. Joint	Reinf. Rib
0	.072	.079
.25	.085	.094
.50	.099	.109
.75	.116	.127
1.00	.134	.146
1.25	.154	.169
1.50	.176	.192
1.74	.199	.219

Stresses in the outer diffuser wall between the expansion joint and the reinforcing rib were calculated using the formulae and rationale below:

$$M_{\max} = \frac{9}{128} wl^2 \text{ at A}$$

$$= \frac{9}{128} \times 8 \times 3.69^2 = 7.66 \text{ in lbs}$$

Maximum stress:

$$s = \frac{M \times 6}{.25^2} = 735 \text{ psi}$$

Maximum deflection: $y = .0054 \frac{wl^4}{EI}$

$$y = .0054 \times \frac{8 \times 3.69^4 \times 12}{17 \times 10^6 \times .25^3} = .00036"$$

Stress at B and C due to largest M_0 , M_1 or M_2 moment: 11,030 in lb:

$$B: S = \frac{11,030 \times 1}{.9535} = 5,101 \text{ psi}$$

$$C: S = \frac{11,030 \times 1}{.8714} = 7,430 \text{ psi}$$

Compared to other stresses and deflections in the diffuser, these values are considered to be minimal, therefore no tables of these values at selected points along the diffuser length were included.

Stresses in the diffuser caused by cooling water pressure were calculated using the formulae and rationale below:

Pressure: 100 psig

.104" wall:

$$M_A = \frac{wl^2}{12} = \frac{100 \times 2^2}{12} = 33.33 \text{ inches}$$

$$S_A = \frac{M_A \times 6}{.104^2} = 18491 \text{ psi}$$

$$M_B = \frac{wl^2}{24} = \frac{100 \times 2^2}{24} = 16.66 \text{ inches}$$

$$S_B = \underline{\underline{9246}} \text{ psi}$$

$$Y_B = \frac{1}{384} \frac{wl^4}{EI} = \frac{100 \times 2^4 \times 12}{384 \times 17 \times 10^6 \times .104^3} = \underline{\underline{.0026}} \text{ inches}$$

.25" wall:

$$M_C = \frac{wl^2}{12} = \frac{100 \times 2^2}{12} = 33.33 \text{ in lbs.}$$

$$S_C = \frac{33.3 \times 6}{.25^2} = 3200 \text{ psi}$$

$$M_D = \frac{wl^2}{24} = 16.66 \text{ in lbs.}$$

$$S_D = \underline{\underline{1600}} \text{ psi}$$

$$Y_D = \frac{1}{384} \times \frac{wl^4}{EI} = \underline{\underline{.0002}} \text{ inches}$$

Expansion joint.

Tensile forces in A and B
due to the water forces:

$$S_A = \frac{1.94 \times 100}{2 \times .104} = \underline{\underline{933}} \text{ psi}$$

$$S_B = \frac{1.94 \times 100}{2 \times .25} = \underline{\underline{388}} \text{ psi}$$

Shear load at C:

$$S_C = \frac{1.5 \times 100}{.125} = \underline{\underline{1200}} \text{ psi}$$

The water pressure stresses and jet thrust forces were calculated using the formulae and rationale below.

The water pressure at the flexible expansion joint puts the heat input wall into a tensile condition with approximately the following forces:

$$2(60'' + 27'') \times (1.625 + .25) \times 100 = 32,625 \text{ lbs}$$

This results in a .104'' wall tension stress of:

$$S_t = \frac{32,625}{2(60 + 27) \times .104} = 1,803 \text{ psi,}$$

resulting in an elongation of

$$y = \frac{P}{AE} = \frac{1,803 \times 68.5''}{17 \times 10^6} = y = .007''$$

small compared to thermal expansion.

However the 20,000 lbs jet thrust puts the wall into compression with a force of 0 lbs at the diffuser exit to 20,000 lbs at the diffuser inlet in a linear variation, therefore the above tensile stress is reduced by 1,105 psi approximately at the inlet.

The thermal expansion dictates the diffuser elongation, with the jet thrust and the water pressure force being very small.

Jet thrust:

Puts linear .104 only in compression: $\frac{20,000}{2(50 + 30) \times .104} \cong 1200 \text{ psi}$

3.5.4.2 Diffuser thermal stresses and deflections are a function of the heat load into the diffuser wall, (see Table 3.4-18 for these values) the thermal conductivity of the material, and the material thickness. The formulae and rationale for determining these stresses and deflections are discussed below.

Thermal stresses are divided for calculation purposes into stresses in the membrane wall and then for the membrane wall/vessel wall combination. The .104" copper membrane wall calculations are as follows.

The largest temperature differential is the 680 m³/hour case at the inlet: Average membrane temperature at 341^oF, with the vessel wall at 104^oF (inlet water temperature):

$$\Delta l = \alpha l \Delta T = 9.8 \times 10^{-6} \times 2 \times 237 = .00465''$$

$$1 + \frac{\Delta l}{l} = \left(\frac{a}{h} + \frac{h}{a} \right) \left(\arctan \frac{h}{a} \right) \frac{\pi}{180}$$

= 1.002325, this is true for

$$\frac{a}{h} = 16.93$$

$$\therefore h = .059''$$

The membrane wall will bow out an additional amount due to ΔT in the wall, computed as follows:

$$R = \frac{t}{\alpha \Delta T} = \frac{.104}{9.8 \times 10^{-6} \times 12.4} = 856'' \text{ giving } h = .0006'' \text{ additional bow.}$$

Thermal stress due to temperature gradient in the .104" copper membrane wall is:

$$S_{TH} = \frac{\alpha E \Delta T}{2} \text{ psi}$$

This formula applied to selected stations along the diffuser result in Table 3.5-15 for cooling water flow rates of 600 m³/hour and 680 m³/hour as indicated below:

TABLE 3.5-15

MEMBRANE WALL THERMAL STRESSES

STATION m	600 m ³ /hour S _{TH} , psi	680 m ³ /hour S _{TH} , psi
0	833	1033
.25	750	956
.50	666	883
.75	641	833
1.00	600	766
1.25	558	716
1.50	525	675
1.74	491	633

NOTE: Stresses above occur only in the longitudinal direction of the diffuser, since the .104" wall will bow-out in the other direction as explained in the discussion above.

Thermal stress due to the temperature differences in the membrane wall/pressure vessel wall combination were calculated, and these values are shown in Table 3.5-16. The stresses shown would only occur if no differential expansion capability was provided for between the membrane wall and the pressure vessel wall. Since provision has been made for this differential expansion, the only load exerted on the inner liner will be the load due to the deflection of the expansion joints.

Expansion joints:

In the worst case situation, i.e., the 680 m³/hour case, the average temperature differential between the membrane wall and the pressure vessel wall is 197°F. The differential expansion resulting from this ΔT is expressed as:

$$\Delta l = 9.8 \times 10^{-6} \times 68.5" \times 197 = .132" \text{ or } .132"/6 = .022"$$

per expansion joint.

The stresses caused by the .022" expansion are:

18,000 psi tensile at Point A

18,000 psi compressive at Point B

TABLE 3.5-16
STRESSES IF NO EXPANSION JOINTS PROVIDED

STATION m	600 m ³ /hour S _{TH} , psi	680 m ³ /hour S _{TH} , psi
.0	35486	40484
.25	33487	35819
.50	31820	33986
.75	30321	32154
1.00	28655	30488
1.25	27489	29488
1.50	26323	27822
1.74	25323	26823

Since membrane wall stresses are low and longitudinal stresses are effectively relieved by the incorporation of expansion joints in the diffuser design, thermal stress is considered to have a minimal impact. The stresses in the expansion joints can be reduced by changing the joint geometry.

3.6 Electrode System Design

3.6.1 Introduction and Basic Description. In a windowframe channel the difference between electrode and insulating walls is obscured since the entire channel is in contact with the gas and can transfer current to and from the gas. But, nonetheless, in a large well designed windowframe channel away from the fringe field and power takeoff, most of the current will be transferred to what would normally be called the electrode walls. Current transfer to the side walls serves mainly to balance and satisfy the current continuity conditions.

Ceramic or slag electrodes with in situ flame spray maintenance via addition of electrode maintenance additives to the combustion chamber will be utilized for the U-25 channel.⁽¹⁾ The purpose here is to discuss the electrode design for maintenance with particular attention to peculiarities of the windowframe design. The electrode maintenance material will cause a coating to exist on all of the walls of the channel, so that during operation the channel is completely lined with maintenance material. The composition of the maintenance materials is selected so that the gas-electrode surface is slagging, i.e., is a

highly viscous liquid which can capture the maintenance materials injected in the combustion chamber and simultaneously is viscous enough so that runoff losses are tolerable.

Single tests of up to two hundred (200) hours, and total electrode lifetimes of several hundred hours were achieved with small (1 kg/sec) windowframe Hall channels using the methods that will be employed. ⁽¹⁾

The electrodes should be thought of as a system, rather than as a component or material. The electrode system is described in Fig. 3-25. The functions of the electrode system are:

- A. To make contact with the plasma so that current can be transferred from the plasma to the channel structure.
- B. To make contact with the base material of the channel structure that is to conduct the current from the gas to the base metal structure.
- C. To provide axial insulation adequate to sustain the Hall field.
- D. To seal the channel from the gas and protect the base metal and other materials of construction from direct exposure to the combustion gases and corrosive effects of condensates. The importance of the sealing function of the slag layer cannot be over-emphasized. It is virtually impossible to prepare a big channel with a thoroughly sealed gas side prior to initial firing. Penetration of condensates from the alkali laden combustion gases into the structure is a notorious cause of MHD channel forced shutdown due to corrosion and/or shorting. Deposition of a dense, vitreous slag layer is the best way to protect the channel from condensate penetration.
- E. To minimize heat loss.

The result of these requirements is that the layer of refractory material between the base metal and the gap must:

- A. Exhibit a surface temperature adequate for good contact with the gas and which provides slagging conditions for capture of maintenance materials.
- B. Have sufficient electrical conductivity to carry the current to the metal electrode base without excessive losses, tunneling (pinching) or breakdown.

Fig. 3-25. ELECTRODE SYSTEM SCHEMATIC

- C. Under current carrying conditions be thermodynamically compatible with the electrode base materials so that the base material is not corroded.
- D. Be thermodynamically compatible with the insulator so that the integrity of the insulator is not compromised.

Items (B) and (C) above are closely connected since the conduction of current through the slag layer can lead directly to corrosion of the base metal at the anode if current is carried by oxygen ions. It should be noted, however, that such corrosion has not been observed in many cases where it might have been expected for pure electrode materials.⁽¹⁾ This is probably due to the inherent oxidation resistance of the Inconel base metal which was employed or to electron conductivity imparted by iron oxide or other impurity in the maintenance material.

Figure 3-25 is intended to illustrate the basic operation of and problems with the electrode system. The gas velocity is to the right and, with the B vector as shown, the transverse current, j_y , is up corresponding to a downward flux of electrons with velocity $V_e = j/n_e e$, where n_e is the electron density and e the electron charge. The top electrode wall is at a positive potential with respect to the bottom wall at the same station. The top wall being an electron emitter is the cathode wall, while the bottom wall, an electron getter is the anode wall. For the windowframe, the diagonal is shown connecting a point on the anode wall with an upstream point on the cathode wall of the same potential.

The electrodes are segmented to prevent gross circulation of Hall current. However, since the surface of each electrode is a conductor, local Hall current can circulate through the electrode as shown on the left. This circulation causes the current to concentrate on the upstream side of the anode electrodes, and on the downstream side of the cathode wall electrodes as shown. In a gross sense, the current concentration leads to Ohmic losses which are of little consequence in a large generator with fine segmentation at modest Hall coefficient. Locally, however, the current concentrations can be extremely troublesome, especially on the anode wall because they can force transverse pinch and the formation of arc spots which can locally overheat the electrode and lead to breakdown through the insulation. Observe that short circuit j_s through an insulator on the anode wall leads to $j_s \times \vec{B}$ forces which push the discharge further into the wall and can destroy the insulator. The loss of insulator integrity on the anode wall is the major cause of forced shutdown of large MHD channels. Conversely, preservation of insulator integrity is the single most important factor in the design of the electrode system. Three factors control the insulator integrity:

- A. The voltage between frames and the power which can be dissipated in a breakdown between frames.

- B. The intensity of the current concentration and effectiveness of methods utilized to reduce that concentration.
- C. Maintenance of low electrical conductivity levels in the insulator.

3.6.2 Interframe Voltage and Breakdown Power Level. Since the frame is normal to the electric field, the interframe voltage, V_f , is given by

$$V_f = \bar{t} \sqrt{E_x^2 + E_y^2} = \bar{t} E_x \sqrt{1 + \phi^2}$$

The object is to minimize V_f and this is simply a question of minimizing the frame thickness t . We have tentatively selected $t = 3/8"$ ($7/16"$ including insulator) for Region 3 and $t = 11/32"$ ($13/32"$ including insulator) for the other Regions where the value of ϕ is being varied as rapidly as possible in order to come normal, or close to it, at the nozzle and diffuser flanges. With these dimensions, the maximum voltage per frame occurs at the 5.90 meter station at the junction of Regions 3 and 4 and has a value of 15 Volts at the design condition. Should detail design indicate that mechanical considerations prohibit this degree of segmentation in the region of rapid wall angle variation, $\bar{t}$ and δ would need to be increased in the same proportion in order to maintain the same $d\phi/dx$. Thus, if minimum frame thickness was increased to $5/16"$, the value of $\bar{t}$ would need to increase to $0.487"$ and t_2 to $0.600"$. V_f maximum would increase by 20% (the same ratio as the increase in thickness) to 18 Volts.

The power level that can be dumped into a breakdown, P_b , can be an important factor in determining whether or not the breakdown will clear itself. Quantitative prediction of failure breakdown power level in given circumstances is not yet possible. However, it is possible to estimate the breakdown power level and compare that level with that of other generators, and the breakdown experience of those units. For small j_x an estimate of P_b is:

$$P_b = 1/4 \Omega \sigma u^2 B^2 (1 - \alpha)^2 t^2 d_1$$

which has a maximum value of 600 Watts for this design. The values of V_f and P_b for this design are compared with those of other generators in the table below.

TABLE 3.6-1

COMPARISON OF V_f AND P_b FOR VARIOUS MHD GENERATORS

<u>Generator</u>	<u>Typical Operating Duration</u>	<u>V_f (volts)</u>	<u>P_b (watts)</u>
Mark II	10 sec	30-40	1200
Mark V	1 min	30-35	7000
LORHO Pilot	3 min	35	1500
LDTF ¹	100 - 200 hr	25-40	25
U-25 (design only)	100 hr	15-18	600

The Mark II did not experience significant breakdown effects except under unusual circumstances. The Mark V, with its design based on the Mark II experience, and with identical electrode pitch, encountered severe breakdown problems which had to be solved before rated net output could be achieved. The huge available breakdown power with the Mark V is undoubtedly the cause, but the problem was unknown at the time the Mark V was first designed. Rated net output power would not have been achieved with the Mark V had there not been a very large safety factor between rated output and what would have been achieved had the breakdown problem not surfaced. The LORHO experienced no breakdown problems. However, the long duration generator with very low damage power would under certain circumstances exhibit sustained breakdown after a considerable period of operation. This could usually be traced to circumstances which allowed alkali to penetrate the insulator.

The endurance data are too skimpy to permit a definitive statement regarding the ability of the present design to achieve 100 hr endurance, but then that is what the program is all about. Both the interframe voltage and breakdown power level are well below that of the LORHO Pilot and the electrode design is based on the methods of Ref. 1.

3.6.3 Current Concentrations. The current concentrations are reduced if a resistive layer covers the surface of the electrode. Thus, a resistive slag layer formed by deposition of injected material will reduce the possibility of pinching and insulator arc-over. Although there will be power dissipation in the slag layer, this loss is partly compensated for by the reduced dissipation in the gas due to the more even current distribution over the slag layer surface. On the other hand, if the conductivity of the slag layer is too high, the layer will apply a partial short circuit to the Hall field.

Consideration of the limiting values of the slag layer conductivity⁽¹³⁾ have shown that if:

$$\sigma \cong AT^n$$

which is typical for a highly viscous slag, where $n \gg 1$

$$V_{SM} \cong \frac{j_s}{\sigma_M^{(n-1)}} \left(\frac{T_M}{T_S - T_M} \right)$$

is an estimate of the voltage drop through the slag layer. Here j_s is the current density and subscripts S and M refer to slag surface and metal interfaces, respectively.

With greater sophistication, it is possible in principle to contour the slag layer thickness over the pitch in such a way as to reduce or even eliminate entirely the current concentrations. Unfortunately, the practical problems in adjusting properly this contouring throughout a generator of significant pressure ratio seems to rule out any attempt to satisfy such contouring conditions in a precise way. Instead, it is most useful to generally follow the rule to present the highest slag layer impedance where the current would otherwise concentrate and conversely offer a low impedance in regions on the electrode segment where the current would be diffuse.

3.6.4 Slag Layer Thickness, Surface Temperature and Estimated Maintenance Material Feed Rates. In view of the complexity of the physical phenomena in the slag layer, a complete analytical treatment of electrode maintenance is a formidable task which has not yet been carried out and will not be attempted here. Such a complete treatment would need to include, but not necessarily be limited to:

- A. Gas phase current distribution in the region adjacent to the electrode wall.
- B. Fluid dynamic motion of a highly viscous slag layer with variable viscosity and thermal conductivity subjected to shear and heat transfer as well as internal Joule dissipation.
- C. Slag layer current distribution with variable resistivity and matching to gas phase current distribution.
- D. Phase equilibria of gas-slag and slag-metal interfaces, as well as diffusion in the slag layer with current transfer.

Analysis of real geometries is even more complicated by the fact that various devices such as screen, grooves, protrusions, etc., are utilized to optimize electrical performance and/or retain the slag layer base.

The coupled gas phase-condensed phase current distribution for a smooth quiescent solid slag layer has been studied in Ref. 14 with very useful results which indicate how the resistive layer can reduce the current concentration, and also indicated lower limits for layer conductivity in a given situation. An approximate analytical treatment of the viscous slag layer with variable viscosity and shear flow, but without Joule dissipation, and for uniform current distribution is reported.⁽¹³⁾ Others have considered the complex thermodynamic problems of the gas-slag interface.

Our objective here is to try to define the approximate conditions under which maintenance will be successful, and obtain estimates of the required feed rates, slag layer thickness and surface temperature. For this, a smooth, stable slag layer will be assumed which is equivalent to stating that protrusions, screens, etc., do not extend to the region where there is appreciable motion of the slag layer. If they do, they will soon burn off in any case (with uncertain consequences). Following this discussion, we will attempt to arrive at electrode geometries which will provide acceptable electrode performance.

3.6.4.1 Required feed rates. The methods of Ref. 13 will be utilized to estimate the fluid dynamic behavior of the viscous slag layer. The analytical results can be arranged to obtain an estimate of the ratio of the maintenance feed rates to gas flow rate (ρ_{sg}/ρ_g) as a function of the other quantities, viz (see Fig. 3-26):

where

$$\frac{\rho_{sg}}{\rho_g} \sim \frac{1}{\mu_s} \left(\frac{kT_s}{\dot{q}} \right)^2 \frac{U}{\eta L} \frac{1}{(n+1)(n+2)}$$

μ_s	is the slag surface viscosity
K	is the slag thermal conductivity
T_s	is the surface temperature
$\dot{q}$	is the heat transfer rate from the gas
U	is the gas velocity
η	is the sticking coefficient, i. e., the ratio of retained maintenance material to the total hitting the surface
L	is the length of the generator
n	is the exponent in $\mu \sim T^n$

Fig. 3-26. Schematic of Wall

Reynolds analogy has been used to derive the above approximate proportionately from Eq. (8) of Ref. 13.

To proceed further, we first summarize the results of Ref. 13 and use these results to estimate the required feed rates.

A. In spite of the relatively large pressure ratio for the generator design that was considered, the calculated surface viscosity:

- 1) varied by a factor of only 2.5 over the entire length of the channel,
- 2) was insensitive to slag composition for slags of widely different characteristics,
- 3) was of mean order ≈ 1.3 poise for $\left(\frac{e_{sg}}{e_g}\right) = 2 \times 10^{-2}$, i. e., the typical concentration for a coal with $\approx 10\%$ ash content (and an extremely large concentration in terms of maintenance) 100% carryover, and oxygen enrichment to $\approx 40\%$ by volume.

B. Because of the very steep variation of μ with T , and the relatively small change in viscosity along the channel, the slag surface temperature, T_s , is nearly constant along the entire channel. Table 3.6-2 below from Ref. 13 illustrates these points and also provides indication of the typical slag layer thickness.

TABLE 3.6-2

SLAG LAYER PROPERTIES

P_a (atm)	3.5	3	2	1	0.5
μ_s (poise)	1.74	1.018	0.77	1.054	1.9
T_s ($^{\circ}$ K) (slag X)	2000	2000	2050	2000	1950
T_s ($^{\circ}$ K) (slag Y)	2300	2350	2400	2350	2250
s (mm) (slag X)	0.43	0.5	0.8	1.5	2.8

For the relatively low pressure ratio for which the U-25 channel is designed, the conclusions with regard to relative uniformity of electrode surface temperature and viscosity should remain valid.

The value of ρ_{sg}/ρ_g for the long duration experiments reported in Ref. 1 were of order 10^{-4} by weight. As the maintenance material considered in Ref. 13 was coal slag in amounts appropriate to 100% carryover with $\rho_{sg}/\rho_g \cong 10^{-2}$, values of viscosity of the order of 100-1000 poise would be required to achieve $\rho_{sg}/\rho_g = 10^{-4}$ assuming all things otherwise equal. As Fig. 3-27 shows, values of critical viscosity of about 100 poise are expected from coal ash. (Similar to castor oil at 0°C .) Although there are no known measurements for the $\text{ZrO}_2\text{-MgO-SiO}_2$ mixture, much higher critical viscosity levels seem likely with the high silica content. The viscosity levels of the hersenite based system are not known at this time.

3.6.5 Selection of Electrode System. The design is flexible as to the precise electrode configuration to be employed since the electrode structure itself is furnace brazed to the frame inside the coolant passage. At the beginning of the Preliminary Design Program, our intent was to utilize an electrode system more or less identical to those utilized for long duration tests in the mid-1960's.⁽¹⁾ This system utilized a magnesia insulator with a zirconia based electrode. In situ maintenance via addition of zircon and natural magnesite was utilized to sustain and seal the gas surface. With small channels, single tests of up to two hundred (200) hours, and total lifetimes of several hundred hours were achieved.

The basic discussion is centered on the use of such a system with MgO insulation and maintenance by zircon and magnesite. However, we would like to retain the option of utilizing a potentially more attractive system that has recently been proposed should this system prove to be attractive after test in a generating situation. This is the system based on hersenite (FeAl_2O_4)⁽²⁾ with the conducting-insulating property adjusted by excess-lean FeO concentration. Surface temperature of $1700\text{-}1800^\circ\text{C}$ would result. With this system, the insulator would be alumina and the maintenance material would be $\text{FeO} + \text{Al}_2\text{O}_3$ with excess FeO to impart conductivity. The system has the advantage of relatively uniform conductivity over a wide temperature range, and would permit the use of a relatively low temperature metal-ceramic interface and insulator. The main question with this system seems to be whether the viscosity will be high enough to achieve acceptable feed rates.

A crucial aspect of the Final Design Program (described in Section IV) is the design, assembly and test of a small MHD channel to verify the in situ electrode system maintenance methods which will be employed. This channel will be operated at an existing MHD test facility. The hersenite based, as well as zirconia based, systems should be examined during these tests.

Fig. 3-27 Viscosity vs Temperature. (Adapted from Coal Ash, "Its Effect on Boiler Availability" by F. G. Ely and D. H. Barnhart, Pg. 831, "Chemistry of Coal Utilization" Ed. by H. H. Lowry, J. Wiley & Son, N. Y. 1963).

With the zircon-magnesite system, the metal contacting the ceramic would be Inconel 600. With the hersenite system, iron would be the contacting material. As shown by Fig. 3-28, Inconel 600 can be operated to above 2400°F (1300°C) in an oxidizing atmosphere without serious oxidation.

3.6.6 Integrity of Electrical Insulator. In simple terms, in order to assure the integrity of the insulator between electrode segments, the absorption or adhesion of materials which destroy the insulating properties, replacement of insulator material by non-insulator, or loss of insulator to the slag layer or gas must be prevented.

The selected insulator material for the zircon-magnesite system is dense magnesia which is flame sprayed on the frames sides prior to assembly of the frames. It should be noted, however, that the thickness of the flame sprayed MgO layer must be adjusted so that on assembly the frame spacing is set by the G-7 or polyimide spacers rather than the MgO. Thus, small gaps will exist in the insulator gas side surface after assembly and these gaps can only be filled to seal off the channel by fixing with maintenance materials but without seed.

Loss of insulator material to the slag layer can be prevented by saturating the slag layer (and maintenance additives) with respect to insulator. Thus natural magnesite 90% MgCO_3 is selected as a maintenance constituent with the following composition:

MgCO_3	90% minimum
CaO	2% maximum
SiO_2	4% maximum
Al_2O_3	1.5% maximum
Fe_2O_3	1.5% maximum

Since the electrode is zirconia based, zirconia is also a constituent of the replenishment material. In order to flux the gas side surface, it is added in the form of zircon, ZrSiO_4 . The magnesia content should be greater than that required to saturate zircon.

In addition to preventing loss of insulator material to the slag layer, diffusion into the slag layer of substances which would lead to unacceptably high electrical conductivity level in the insulator must be prevented. Such substances include the alkali seed (perhaps in company with silica), and/or possibly the iron

Fig. 3-28. Oxidation Properties of Various Materials

impurity in zircon and magnesite. Thus penetration of these materials into the insulator and the resulting effect on the insulating properties of the magnesia should be considered.

An important variable under control is the oxygen concentration at the electrode. Since the U-25 can be operated from 90% theoretical oxygen (rich) to very lean, the oxygen concentration at the electrode surface at approximately 1940°K can be controlled from say 10^{-4} - 10^{-5} to 10^{-1} by volume. Conversely, at low oxygen concentration, relatively large amounts of CO and H₂ will be present.

3.6.6.1 Insulator chemistry. Magnesia is an excellent insulator⁽¹⁵⁾ and there are data to evaluate the reliability of the insulator with respect to corrosion loss, and deterioration of the electrical insulating capacity due to alkali or iron penetration in the bulk and at grain boundaries. Slag-insulator interactions with the maintenance material (zircon + magnesite + iron oxide) can only be estimated; phase equilibria at the temperatures of interest (1100°K at the interface) have not been determined. However, using the low temperature compatibility triangles determined by Foster⁽¹⁶⁾ for MgO + SiO₂ + ZrO₂ that for MgO · FeO · SiO₂,⁽¹⁷⁾ the MgO · SiO₂ · TiO₂ system (ibid p. 249); the MgO · SiO₂ · CaF₂ system (ibid p. 477); and the MgO · SiO₂ · Al₂O₃ system (ibid p. 246), it is reasonable to conclude that a mix of zircon with 60% weight Magnesia would give MgO or Mg₂SiO₄ as coexisting phases at temperatures well above the desired controlled interface temperature. At 40% MgO, Hirano, et al⁽¹⁸⁾ report that Zircon is decomposed into Mg₂SiO₄ or MgSiO₃ and a cubic zirconia in the temperature range above 1050°C which would indicate that the compatibility triangles reported by Foster are not valid at higher temperatures. We might then anticipate that MgO(ss), MgSiO₄ and cubic ZrO₂ (0.85 ZrO₂ · 0.15 MgO) would coexist in the deposited layer. Since MgSiO₄ is a good insulator we do not anticipate problems due to its possible presence. The amount of magnesite to be added to the maintenance material puts the net composition on the MgO side of the join between cubic zirconia and Mg₂SiO₄.

The presence of Fe impurity in the magnesite feed as well as that formed from oxidation of the electrode wall be divalent with a near neutral flame stoichiometry. Therefore, we are also concerned about the reactions between FeO and MgO or FeO and Mg₂SiO₄. As shown in that system, continuous solid solutions exist between MgO-FeO as well as between Mg₂SiO₄ and Fe₂SiO₄. Therefore, penetration and electrical degradation by iron diffusion must be estimated for the channel test interval (100 hours).

Diffusion of Fe and other transition elements into single crystals and at grain boundaries of MgO has been well documented.⁽¹⁹⁾

In single crystals of MgO, the trivalent species of Fe, Co and Ni all diffuse orders of magnitude faster than do the divalent cations. This difference is governed by the need in ionic substances to compensate bivalent impurities

with lattice defects. Thus, two trivalent iron ions cause the formation of a magnesium ion vacancy; the increased vacancy concentration and association with Fe^{3+} causes much more rapid Fe^{3+} diffusion than is the case for Fe^{2+} . (Because Fe^{2+} can occupy an Mg^{2+} lattice site with no charge discrepancy.) Even considering the worst case, extrapolation of the Fe^{3+} diffusivity to lower temperatures gives a value less than 10^{-10} cm^2/sec . The time (t_r) required for penetration through one millimeter thickness of MgO (the design thickness of the insulator) is⁽²⁰⁾

$$t_r = x^2 D,$$

which gives $t_r = 10^6$ sec. By controlling the flame stoichiometry to maintain Fe^{2+} , the penetration time would be even longer.

Grain boundary diffusion and transport at pores would be more rapid than in the crystal. Cobalt and Nickel diffusion in MgO boundaries have been reported by B.J. Wuensch and T. Vasilos,⁽²¹⁾ and shown to be due to SiO_2 and CaO impurities. Since these are common to the system of interest, those data may also be used to estimate the expected Fe penetration for our purposes. The lowest temperature of measurements was 1200°C ; they observed $100\text{ }\mu\text{m}$ penetration along the boundary and $75\text{ }\mu\text{m}$ lateral transport in a 500 hr anneal. Assuming an activation energy of 30 kcal/mole $^\circ\text{K}$ for impurity controlled transport at the boundary, the diffusivity would be decreased by two orders of magnitude (at 1000°K) giving one order of magnitude lower penetration ($0.0004''$). Furthermore, the concentration at that depth was documented as 0.1%, an iron impurity concentration which does not cause gross degradation of the resistivity of MgO.⁽¹⁵⁾ A conductivity level of 10^{-7} $\text{Ohm}^{-1}\text{ cm}^{-1}$ at 1000°C for MgO crystal containing 0.07% Fe with $12\text{ atm} > \text{PO}_2 > 10^{-15}\text{ atm}$.

Insulator-K seed interactions. For small contents of K_2O , the work on K_2O -MgO- SiO_2 equilibria⁽²²⁾ show MgO or Mg_2SiO_4 as stable phases with a multiplicity of compounds in the overall diagram. Since MgO refractories invariably contain some SiO_2 impurity at the grain boundaries, the penetration by K_2O would be expected at long times. However, its influence for this design will be reduced because the hot face of the slag will tend to keep K_2O from condensing. Transport of some K_2O into the silica layer at the grain boundaries might be expected to cause shorting between electrode frames since it is well known that alkali silicate glasses are (alkali) ionic conductors. However, it must be noted that Fe electrodes are not reversible electrodes for K^+ ; therefore, the ionic current would develop a space charge due to the DC field between frames as a transient but would not contribute to steady state current flow. That is to say, that any K that penetrates the insulator should be plated out on the upstream frame.

3.6.7 Mechanical Design of the Electrode System. A conceptual design of the electrode system is shown in Figs. 3-29 and 3-30. It should be emphasized that more detailed calculations and check-out of these configurations in the maintenance test rig will be required before finalization of the electrode configuration. In addition, the possibility for use of the hersenite system needs to be considered. The channel design is flexible with regard to the metal-ceramic interface. A great variety of configurations can be furnace brazed to the basic frame structure.

A tentative knurled electrode structure is shown for two locations in the channel. The knurled structure is intended to perform the functions of slag layer retention and is compatible with high production rates for frames. The actual shape of the knurl could be optimized during the experimental program with the maintenance test channel. For both locations, the sketches assume the maximum rate of wall angle variation, i.e., the maximum difference in frame thickness at either end. The first of the two locations is the selection immediately upstream of $x = 1.4$ m where the angle of the frames with the vertical is a maximum of 50° , and the wall angle is being changed at the maximum rate. The second location is the downstream end of the channel where the rate of wall angle variation is also maximum, but the frames are normal to the direction of the flow.

At the $x = 1.4$ m station with the frames inclined 50° to the vertical, the electrode pitch on cathode and anode walls is 0.488 and 0.780", respectively. At the 6.95 m station, the pitch is 0.500 and 0.312 with the frames normal to the flow. The converse is true for the anode. At both anode and cathode, we have endeavored to maintain the temperature at the insulator-slag layer interface at a low value which will inhibit diffusion of corrosive materials into the insulator. Examination of previous long duration tests would indicate that one of the problems was the attempt to maintain a narrow insulator spacing all the way to the gas surface. The high temperature achieved by the slag layer surface inhibits diffusion of alkali into the insulator which is remote from the slag surface. With the insulator well back from the surface and adjacent to low temperature material of high thermal conductivity, the tendency to absorb contaminating materials by diffusion should be reduced. The gas side temperature should be in the vicinity of 1940-2000°K which should inhibit absorption of potassium into the slag layer.

SCALE 2" = 1"

Fig. 3-29 Potential Electrode Geometry Diffuser-Channel Interface
Maximum Turning Rate $\alpha = 6.95\text{m}$

Fig. 3-30 Potential Electrode Geometry Maximum Equipotential Angle
Maximum Turning Rate $x = 1.4m$

3.7 Channel Design

An important part of the preliminary design program has been to define the methods of construction of large variable wall angle windowframe channels.

With variable wall angle, the chief mechanical questions to be answered can be identified as:

- A. The methods of assembly of the channel.
- B. Frame design.
- C. Sealing.
- D. Handling.

Each of the four items mentioned above will be discussed in detail in Paragraphs 3.7.1 through 3.7.4 below.

3.7.1 Channel Design and Assembly. The most ideal method of construction for a windowframe channel would be to completely wrap the frames in a bonded glass reinforced cloth or woven enclosure, as is done with solid fuel rocket casings and nozzles. Such construction, for instance, has been proposed for lightweight, variable wall angle solid fuel MHD generators by MEPPSCO, as well as for lightweight, airborne liquid fuel generators. The disadvantage of such construction, however, is that the channel cannot be disassembled. In view of the developmental character of the U-25 channel, it is felt that the ability to disassemble the channel without essentially destroying it is a vital feature of the construction. Therefore, the optimum bonded fiber wrapped construction was not employed here, and the channel will be bolted together as appropriate.

In addition, an important factor for this particular channel is the need to define a method of increasing the length of the channel when tested at AEDC where the length of the magnetic field is 0.9 meters longer than in the U-25. This feature is easily accomplished for a windowframe design by simply adding more frames, as was done previously to modify the loft and extend the length of the original LORHO channel.

The channel which is approximately twenty-three feet long for the U-25 installation, and about twenty-six feet long for the HPDF, makes it necessary to construct it in a number of sections. Previous Faraday channels of this magnitude were built in single section and were extremely difficult to modify and to handle. Additionally, construction is simplified since the entire channel does not have to be tested to maximum inlet pressure. The U-25 channel will be built in twelve (12) sections. The channel construction is such that each section can be disassembled for servicing or modification.

The channel is a rectangular duct made of trapezoidal shaped frames. Each frame is insulated from its neighbor by a plastic gasket which also acts as a seal to prevent the gases from leaking out of the channel. The frames are bolted to each other to form sections. The first and last plate in each section is modified to form a flange. These flanges are used to bolt the sections together to form the channel. See Fig. 3-31 for an artist's concept of a typical channel section.

The spacing of the bolts is determined by the pressure required on the gasket in order to achieve a seal. The number of plates joined together by a single bolt is a function of the angle and width of the plates for the side bolts, and the spring rate of the gasket for the top and bottom bolts. Each bolt will be insulated from the plates by insulating sleeves and washers.

The bolting arrangement for both the sides of the channel and the top and bottom will be the same and will consist of bolting one frame to the next. Figure 3-32 illustrates a typical bolting arrangement in which Frame A contains a tapped hole, Frame B contains a clearance hole for the shank of the bolt, and Frame C contains a clearance hole for the head of the bolt. Therefore, each frame will contain groups of holes, i. e., a tapped hole, a shank clearance hole, and a head clearance hole. These groups of holes will be equally spaced around each frame, with the pitch being dependent upon the bolt spacing required to achieve a gas seal. A further expansion of this bolting arrangement is indicated in Fig. 3-33, Exploded View of Bolting Arrangement.

With this design it is envisioned that each plate would be assembled into its section using an assembly fixture. This fixture will assure that the end flanges of the sections are parallel to each other. It will also assure that the flange mounting holes are in line with the axis of the channel so that when all the sections are bolted together to form the channel, the flanges that mate with the Soviet interfaces are within the tolerances specified in the interface documents.

In order to hold the tolerances necessary to assure that the flanges will be parallel and square, it is anticipated that each frame will be used as a drilling fixture for its mating frame. Using this method, a mounting flange will be placed into the fixture which will have pre-drilled locating holes to locate the flange true with respect to the axis of the channel. Next, a gasket will be cut out using the next plate as a pattern. The plate and gasket will then be correctly located on the fixture and used to match drill a suitable size hole which will be threaded. Also at this time the dowel holes will be drilled and reamed and the plastic dowels inserted. This process will continue through the whole section ending with another flange. See Fig. 3-34 (Drawing No. U-25-1297) for relative locations of dowels and bolting orientation.

MEPPSCO

Fig. 3-31. Typical Channel Section

Fig. 3-32. Typical Bolting Arrangement

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MEPPSCO

Fig. 3-33. Exploded View of Bolting Arrangement

Fig. 3-34.

CHANNEL FLG DETAIL

U25-1297

The end flange will be ground to suit to compensate for angular deviations of the frames and gaskets throughout the length of the section. Utilizing this method, we expect to have the flanges of a completed section parallel to each other within .005 of true indicated reading, and the hole true positioned to the axis of the channel within .010. Figure 1-6, in addition to showing coolant manifolding, also depicts the fully assembled channel as installed in the U-25 facility.

3.7.2 Frame Design and Assembly. With the U-25 generator channel operating over a substantial pressure ratio and change in wall angle, each of the several hundred frames comprising the channel is different in shape. Each of the frames will see a voltage difference between itself and its neighbor, ΔV , given by:

$$V = E_x t (1 + \phi^2)^{0.5}$$

where t is the thickness of the plate. The value of $\Delta V/t$, i.e., the net electric field, is shown as a function of axial station. It is seen that this quantity is nearly constant over the entire length. Thus, it is reasonable to use a uniform plate thickness throughout the generator. A tentative plate thickness of 3/8" with a 1/16" insulation was selected. This gives approximately 17 Volts maximum interplate voltage difference.

Since each of the several hundred plates is different, it is important to systematize the design of these plates. The angle between the equi-potential and the vertical changes from the value of 50° at the inlet of the active section, to a value of 23° at the exit of the active section. Additionally, the wall angle is pitched up to 0° between the inlet of the active section and the nozzle flange (0.7m), as well as between the active section and the diffuser flange (0.9m).

The inside surface of the plates is described by the aerodynamic loft prescribed for the channel, the form of $D_1(x)$ and $D_2(x)$. These were described in the form of 5th order polynomials based on the design calculations. The plate design problem is illustrated in Fig. 3-35. In plan, each plate runs upstream from the value of x , where it intersects the positive wall, through the axial station at the channel centerline which is used to designate the plate, and to the negative electrode wall at the downstream intersection. Thus, the plan view of each plate is given by the intersection of the two polynomials for $D_2(x)$ with the straight line through the position of the center of the plate. Since ϕ is varying, the upstream and downstream edges of the plate are not parallel, i.e., the plate is tapered in order to change ϕ .

In the most ideal construction, the wall angle would be changed with every plate since this would most closely duplicate the design. On the other hand, it would be desirable to minimize the number of tapered plates for machining and fabrication. If all plates are tapered, the taper angle is 4-6' or approximately 1/16" difference in thickness between the two ends. This is about all that

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Fig. 3-35. SKETCH ILLUSTRATING PLATE DESIGN PROBLEMS

can be accepted with 1/4" water passages and 3/8" plates. Thus, all plates must be tapered.

At each intersection of the line through x with the curve for $D_2(x)$ the frame will have the width appropriate to D_1 at that station. Since the value of D_1 is an increasing function of x , the two ends of the frame will have different heights. In between the two ends, the frame most ideally would have a height appropriate to the value of D_1 at the local angle station through which the frame is passing. If this were the case, the sides of the frames would be curved. Such a construction is deemed to be impractical. Instead, the shape of the frames is approximated by a trapezoid, with the ends of the trapezoid having values of D_1 appropriate to the value of D_1 at the axial station where they intersect the loft. Since the second derivative of D_1 with respect to x is positive in the active region of the channel, the trapezoid approximation tends to bulge the channel slightly at the center over the ideal value of D_1 for that station. The amount of this bulge is of the order of .010 to .015" and is considered to be negligible. The wall will be somewhat rough in any case due to electrode retention grooves, and the bulge due to the trapezoid approximation should not effect operation significantly.

In order to systematize the design of these plates a computer program was written. This program calculates the dimensions of a frame as well as the axial station to be assigned to the plates. Note that in general with a variable wall angle the number of plates must be computed. Table 3.7-1 shows a portion of the relevant frame data for a number of typical frames. The parameters are displayed in Fig. 3-36. The distance to the axial intersection of the front face of each frame is specified by " x ". Distances " x_1 " and " x_2 " respectively are the axial positions of the centers of the intersections of each frame with the gas line. Angles " α " and " β " are equal to the sum of " Θ " and the slope angle at the top of each frame and the difference between Θ and the slope angle at the bottom of each frame respectively. Thus angle specification is more convenient for actual construction purposes. Assuming that the frames are trapezoidal in shape, lengths " d_{11} " and " d_{12} " are the bases of each trapezoid taken at the axial positions " x_1 " and " x_2 " respectively. The program can easily be extended to provide more details of plate design, and this will be done during a final design of the channel. Such a method will be very convenient since the computer can directly produce a tape which will then be used on a numerically controlled machine to fabricate the plate automatically.

A number of different approaches to the fabrication of these frames have been considered. Some of these approaches with their attendant advantages and disadvantages are discussed below:

- A. Approach #1 considered cutting the frames out of a solid plate and gun drilling the water holes. As there are no welds, this method is the most reliable. However, because of the gun drilling and machining plus the waste of the inside blank, it is very expensive. In addition, a method to permit the water passage to track corner radii in the gas side must be devised.

TABLE 3.7-1
FRAME DESIGN PARAMETERS

Frame No.	θ		X meters	X ₁ meters	X ₂ meters	h meters	d ₁₁ meters	d ₁₂ meters	α		β	
	Deg.	Min							Deg.	Min	Deg.	Min
1	22	15	.1490	.3033	.0018	.7947	.3332	.3233	22	15	22	15
10	25	20	.2504	.4283	.0304	.8109	.3428	.3309	25	20	25	20
20	28	39	.3661	.5704	.1700	.8329	.3483	.3336	28	39	28	39
30	31	53	.4354	.7173	.2626	.8592	.3543	.3367	31	53	31	53
40	35	0	.6089	.8698	.3533	.8901	.3605	.3401	35	0	35	0
50	38	0	.7371	1.0286	.4577	.9253	.3670	.3439	38	0	38	0
60	40	53	.8705	1.1945	.5609	.9667	.3735	.3479	40	53	40	53
70	43	39	1.0097	1.3685	.6635	1.0130	.3801	.3523	43	39	43	39
80	46	17	1.1553	1.5515	.7806	1.0654	.3865	.3569	46	17	46	17
90	48	48	1.3079	1.7446	.8978	1.1242	.3929	.3617	48	48	48	48
100	49	55	1.4724	1.9297	1.0470	1.1536	.3935	.3677	49	55	49	55
110	49	17	1.6440	2.0955	1.2260	1.1474	.4032	.3747	50	39	49	17
120	48	38	1.8134	2.2593	1.4022	1.1423	.4076	.3813	50	5	47	46
130	47	58	1.9806	2.4210	1.5756	1.1382	.4117	.3873	49	29	46	56
140	47	18	2.1456	2.5806	1.7466	1.1349	.4157	.3929	48	53	46	9
150	46	37	2.3036	2.7382	1.9152	1.1323	.4195	.3981	48	16	45	21
160	45	56	2.4695	2.8937	2.0816	1.1302	.4234	.4028	47	37	44	34
170	45	15	2.6284	3.0471	2.2458	1.1285	.4274	.4072	46	53	43	38
180	44	33	2.7854	3.1936	2.4080	1.1271	.4316	.4114	46	18	43	2
190	43	50	2.9405	3.3481	2.5683	1.1260	.4360	.4153	45	37	42	15
200	43	7	3.0938	3.4956	2.7268	1.1251	.4403	.4193	44	56	41	29
210	42	23	3.2452	3.6413	2.8834	1.1244	.4458	.4232	44	14	40	42
220	41	39	3.3949	3.7851	3.0383	1.1238	.4513	.4272	43	32	39	56
230	40	54	3.5429	3.9271	3.1916	1.1234	.4572	.4314	42	49	39	9
240	40	9	3.6892	4.0674	3.3433	1.1231	.4635	.4359	42	5	38	22
250	39	23	3.8339	4.2060	3.4935	1.1230	.4703	.4407	41	22	37	34
260	38	37	3.9770	4.3429	3.6421	1.1230	.4776	.4459	40	38	36	46
270	37	51	4.1186	4.4782	3.7893	1.1232	.4853	.4515	39	54	35	59
280	37	3	4.2587	4.6120	3.9351	1.1235	.4934	.4575	39	10	35	8
290	36	16	4.3973	4.7442	4.0795	1.1241	.5019	.4641	38	25	34	20
300	35	27	4.5345	4.8750	4.2226	1.1249	.5107	.4712	37	41	33	28
310	34	39	4.6703	5.0044	4.3644	1.1260	.5197	.4783	36	57	32	38
320	33	50	4.8048	5.1324	4.5049	1.1274	.5290	.4869	36	12	31	46
330	33	0	4.9380	5.2591	4.6442	1.1291	.5384	.4954	35	28	30	53
340	32	10	5.0700	5.3844	4.7824	1.1313	.5479	.5044	34	43	29	59
350	31	19	5.2008	5.5086	4.9193	1.1338	.5572	.5137	33	59	29	4
360	30	28	5.3303	5.6315	5.0552	1.1368	.5665	.5234	33	15	28	8
370	29	37	5.4588	5.7533	5.1900	1.1403	.5754	.5333	32	31	27	12
380	28	45	5.5861	5.8740	5.3237	1.1444	.5839	.5433	31	47	26	15
390	27	53	5.7124	5.9935	5.4564	1.1491	.5919	.5533	31	4	25	16
400	27	0	5.8377	6.1120	5.5882	1.1544	.5993	.5632	30	21	24	16
410	25	17	5.9574	6.2137	5.7235	1.1495	.6050	.5732	28	47	22	24
420	22	43	6.0705	6.3002	5.8609	1.1400	.6120	.5830	26	33	19	42
430	20	6	6.1815	6.3846	5.9963	1.1329	.6130	.5921	23	56	16	55
440	17	25	6.2906	6.4676	6.1300	1.1312	.6140	.6003	21	16	14	2
450	14	43	6.3930	6.5482	6.2620	1.1352	.6150	.6115	18	34	10	52
460	11	59	6.5042	6.6271	6.3934	1.1368	.6160	.6131	15	49	8	9
470	9	13	6.6092	6.7048	6.5244	1.1407	.6170	.6147	13	3	5	23
480	6	25	6.7134	6.7813	6.6553	1.1471	.6179	.6164	10	16	2	35
490	3	37	6.8170	6.8569	6.7862	1.1561	.6188	.6180	7	27		13
500	0	48	6.9203	6.9317	6.9177	1.1677	.6198	.6196	4	39	3	2
502	0	14	6.9410	6.9466	6.9440	1.1704	.6200	.6199	4	5	4	5

FIG. 3-36. FRAME CONSTRUCTION PARAMETERS

- B. Approach #2 considered cutting frames out of a solid plate, machining grooves, and brazing coolant tubes in place. This approach is somewhat less reliable than Approach #1 due to the brazing of the tubing to the frame. It could however be a slightly more cost effective approach than #1.
- C. Approach #3 considered making the frames out of extruded stock and brazing or welding at the four corners to form a frame. Although this may be a relatively low cost approach, its major drawbacks are:
 - 1. The inside corners of the frame are square, thus creating a stress problem.
 - 2. There is a larger pressure drop at the intersection of the water passages where the frames are joined together.
 - 3. To date we have not been able to identify anyone who can extrude this cross section.
- D. Approach #4 considered making the frames out of a combination of extruded stock and cast corners. Although this approach might be less costly than those above, it also has some major drawbacks which are:
 - 1. Availability of the extrusions.
 - 2. The small area available for joining at the intersection of the cast corners and the extruded sections.
 - 3. Potential for high scrap rate due to difficulty in joining extruded stock and cast corners.
- E. Approach #5 considered making the frames out of roll-formed bar stock and brazing the cooled wall section and gas side onto the inside surface of the frame. This is a relatively low cost construction approach which also offers the capability of separating the cooled wall section of the frame from the support portion of the frame. This approach might prove to be advantageous if the thermal stresses are high.

It appears at this time that Approach #5 is the most feasible and economical means of fabricating the frames.

Assuming that Approach #5 is selected as the final approach, which requires welding and/or brazing, the fabrication technique would require that the following operational sequence be utilized:

- A. Roll forming frames from bar stock.
- B. After welding, suitable heat treatment would be required for stress relieving.
- C. Upon completion of stress relieving, the frame would be machined by numerically controlled machines which receive their input from the computer programs generated for the frame design.
- D. The next operation would consist of forming the electrode and cooling sections followed by the welding or brazing of these sections to the support frame.
- E. Following brazing or welding of the electrodes and cooling section to the support frame, the unit would again require suitable heat treatment for stress relieving.
- F. The final operation would be Blanchard grinding of the whole assembly to acquire the required surface finish for the gasket sealing faces and to achieve the correct angle in the plates.

Modification will be required for certain frames at prescribed locations along the axis of the channel to provide for data gathering instrumentation. The modification of these frames will be accomplished subsequent to the operations discussed above. Figure 3-37 shows a frame modified for pressure tap insertion. This same type of access hole can be used for a thermocouple mounting adapter. Figure 3-38 shows a frame modified to provide a means for checking current flow.

3.7.3 Sealing Design and Assembly. It is desirable to minimize spacer-seal thickness to minimize the voltage difference between frames and temperature rise of the insulator at the electrode surface. The latter is important for minimizing diffusion of undesirable impurities into the insulator. On the other hand, due to the large total length of seal, it is necessary to assure seal integrity.

"O" ring or gasket seals have been considered. The "O" ring provides the most positive seal, while the gasket provides minimum spacing with straightforward frame construction.

Fig. 3-37. FRAME MOD. FOR PRES TAP

FULL HILL

Fig. 3-38. FRAME MOD FOR CURRENT MEASURE

To utilize standard "O" ring sealing techniques, the "O" ring grooves could be machined into each side of every plate as shown in Fig. 3-39(a) (electrode surface is not detailed here). Bolted construction is assumed. Since the groove depth must be held to a $\pm .001$ tolerance, the groove will have to be cut after all other plate machining has been completed. This will be very expensive, but is an option to be considered if expense is not a factor.

Another variation on this method is to have the "O" ring groove extruded during the frame extrusion process. This would result in large variations in the groove depth. Since a solid "O" ring requires close control over groove depth, a solid "O" ring could not be used. If however, a fluid seal is injected into the groove after the plates are assembled into a module, then the "O" ring groove depth would not be as critical. Silicone might be used as the sealing material in this case.

A third variation on the "O" ring sealing technique is shown in Fig. 3-39(b). Here the "O" ring grooves are machined in the spacer, which must be at least 0.125" thick. To minimize insulator thickness at the surface, the water tube overlaps the frame base as shown, complicating frame construction.

Typical gasket sealing technique is illustrated in Fig. 3-39(c). The gaskets are cut from relatively hard flat stock.

A major factor in gasket joints is the force required to achieve a seal since this force is a function of the spring rate of the gasket and the area of the gasket. Also, the force applied to this gasket is proportional to the size and number of bolts used to make the assembly. Thus, the stiffer the gasket the greater the number of bolts required.

3.7.4 Channel Handling. Channel handling may be considered as having two distinct areas of concern. They are handling required during initial assembly operations and field handling of components and the completely assembled channel system. Fixtures required for initial assembly were discussed in Paragraph 3.6.1 above, therefore will be discussed here only with the relationship to further extension of their usage. The remainder of this discussion will be centered around the total handling concept.

As discussed in Paragraph 3.6.1, each section of the channel must be mated with its matching sections within very precise tolerances. This is necessary due to the requirement for shear pins at each flange interface. Fixturing will be used to align these sections prior to machining the holes for the shear pins, and also to assure proper alignment of adjoining sections. Inasmuch as these fixtures are required for initial assembly, it would appear that they could also be used for field assembly of the sections. There is no requirement for the fixture to be mobile for the machining or initial assembly operation. When used in the field, however, mobility will be mandatory as the fixture will not only be used

—————
 Fig. 3-39 (a) 2/1 J. CHANCLER
 ————— "O"-RING SEALING TYPICAL
 using Grooves in Frames
 ————— 7 FEB 75 U25-1315

Fig. 3-39 (b)

2/1

F.P.

"O-RING SEALING TYPICAL
using Grooves in Spacer

7 FEB 75 U25-1317

Fig. 3-39 (c)

2/1

F.P.

GASKET SEALING TYPICAL

7 FEB 75 U25-1316

for assembly but will be used to support the fully assembled channel system before it is installed into the magnet. When used in the AEDC facility, the channel system will be supported on integral Thompson Roundway bearings and the fixtures will be equipped with rails that will interface with the AEDC magnet rails. When used in the Soviet magnet, the Thompson Roundway bearings can be removed from the bottom of the channel and attached to an intermediate structure which will be used to support the sections of the Soviet channel. Using this method, the sections of the channel can be supported separately for assembly in either the AEDC facility or the Soviet facility using the fixture. It is very likely that, due to its size and weight, the fixture will have to be built in sections.

There are three major areas of concern relative to field handling of the equipment. They are:

- A. Shipping of the channel from point of manufacture to the AEDC facility.
- B. Handling of the channel at the AEDC facility.
- C. Shipment of the channel, assembly, and installation into the magnet of the U-25 facility.

3.7.4.1 Shipping of the completed channel components, nozzle, and diffuser from the point of manufacture to the AEDC facility can be handled by either of two methods. The first method would be to ship the nozzle, diffuser and each of the twelve (12) individual sections of the channel attached to its individual segment of the assembly fixture. Air freight shipment is contemplated, and it is not known at this time whether weight and size limitations will preclude the use of this method. If this approach is feasible however, it could appreciably decrease assembly time at the AEDC facility as the segments would already be installed to the assembly fixture. The second method would consist of shipping the components and the fixture separately, either crated or palleted. This would be a more time consuming approach as the units would have to be affixed to the fixture before final channel assembly could begin.

3.7.4.2 Handling of the channel at AEDC is expected to fall into the following pattern. Upon arrival at AEDC the channel will be assembled with refractory material installed in each of the section joints. The assembly of the channel, and attachment of the nozzle and diffuser sections will be accomplished utilizing the fixture discussed above. The channel system, being supported by the fixture, will then be rolled out to the magnet. After proper alignment of the fixture and magnet rails is accomplished, the channel system will be released from the fixture and rolled into the magnet on its integral Thompson Roundway bearings. Mechanical connections to the combustion chamber and AEDC diffuser as well as the cooling water system will then be made. Data gathering instrumentation will also be connected at this time. Removal and disassembly of the channel

for shipment to Moscow would be a reversal of this procedure. It is assumed that any necessary cranes or lifting equipment required will be readily available at the AEDC facility.

3.7.4.3 The sequence of events depicted for shipment, assembling and handling of the channel in the U-25 facility is predicated upon the assumption that the assembly and maintenance area will have had all necessary tools, etc., installed and that the area will be ready for operation before the channel arrives. All components of the channel and fixture used at AEDC will be shipped by air freight from Tullahoma, Tennessee to Moscow. The fixture intermediate structure components will be air freight shipped from point of manufacture to Moscow. All of these units will be broken down to a suitable size for shipment and either palletted or packaged in containers. Upon arrival in Moscow, the channel sections, nozzle and diffuser will be assembled into a complete system on the supporting fixture. This assembly task will be accomplished by the U.S. field team. When fully assembled, the channel system will be rolled out to the immediate vicinity of the magnet. In the magnet area, a lifting beam will be attached to the channel unit and the overhead crane. After the beam and crane have been attached, the fixture intermediate structure will be disconnected from the channel. The Soviet crane operator and riggers will then position the channel in the magnet. The lifting beam will be removed and mechanical connections will be made to the combustion chamber, the Soviet diffuser section and the cooling water supply. Data gathering instrumentation will be connected and the top half of the magnet re-installed. Figures 3-40 through 3-44 show an artist's concept of the sequence of events for channel installation in the U-25 magnet. Figure 3-40 shows the U-25 magnet assembled with no channel present. Figure 3-41 shows the same magnet with the top half removed for installation of the channel. Figure 3-42 shows the channel, supported by the lifting beam, being lowered into position in the bottom half of the magnet. Figure 3-43 depicts the cooling water manifolding as connected at the U-25 facility. Figure 3-44 shows the channel fully assembled into the U-25 magnet with the diffuser flange in the foreground. Removal and disassembly will be essentially a reversal of the assembly and installation process.

As discussed in the Program Plan Section of this report, forced shutdowns may be expected during the test program. These forced shutdowns can be categorized as minor, intermediate, or major in nature. A minor shutdown would be one where the problem can be solved without having to remove the channel from the magnet or disassembling any of the major channel units. An intermediate forced shutdown would be one where the channel must be removed from the magnet, partially disassembled and the problem solved locally. A major forced shutdown would be one in which any of the channel major components would have to be removed and returned to the U.S. in order to solve the problem. During the detailed design phase of the program, an exhaustive analysis will be conducted to provide a spare parts and materials list of items required to assure that an absolute minimum of forced shutdowns would be considered to be of a major nature. Further, all drawings in the final design phase will contain both U.S. and metric measurements to allow fabrication of certain components within the Soviet facility if required.

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Fig. 3-40. U-25 Magnet Assembled Without a Channel Installed

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Fig. 3-41. U-25 Magnet Top Half Removed

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Fig. 3-42. Channel Being Lowered into U-25 Magnet

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Fig. 3-43. U-25 Channel with Cooling Manifold Connected

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Fig. 3-44. U-25 Channel Installed in Magnet

SECTION IV

PROGRAM PLAN AND SCHEDULE

4.0 PROGRAM PLAN AND SCHEDULE

4.1 General Information

This section of the Report provides a Program Plan and Schedule for the detail design, fabrication, and testing effort for the U-25 channel. It has been made a free-standing section of the report to allow easy removal for use by personnel who may not require use of the total report. This program plan and schedule are presented to provide planning information to OCR so that they may coordinate the program with the Soviets, incorporate the program into their own activities and provide the necessary funding for completion of the U-25 program. Section 5 of the report under separate cover presents a cost estimate for the program plan and schedule described in this section. In addition to detail design and fabrication activities, this section provides a description of the personnel requirements in the field and a preliminary description of the supporting facilities which will be required at the U-25 facility in Moscow.

A proposed modification to the program whereby two channels would be utilized is also discussed. It is believed that this modification would offer greater advantages and flexibility to the overall OCR program than is available with only one channel. It would provide another channel which could be continuously tested in parallel with the U-25 test program for shorter duration and high field strengths at the Arnold Engineering Development Center. In addition, the use of a second channel would permit early test results at AEDC to influence final fabrication of the channel for the U-25.

The program plan and schedule presented here are predicated upon the assumption that the contractors to whom OCR has assigned responsibility for the program will be able to carry it out in a forthright and uninterrupted manner. In a program such as this, the final design process almost always brings out problems which generally must be resolved by changes. Each change will most likely effect, to some degree or another, the performance of the generator. It is felt that the contractor must have the latitude to make such changes. The schedule does not include allowance for multiple, lengthy review hiatus.

A concrete example of the above discussion which will probably arise during the final design is the integration of the mechanical features of variable wall angle construction of the generator with the aerodynamic performance of the channel. It is almost a certainty that the final design process will reveal that certain modifications to the wall angle variation and plate thickness, described in Section 3.0 of this report, will be required. A contractor should be authorized to make these changes in the interest of the overall program. This should not, however, relieve the contractor of responsibility for notifying OCR of the changes. Once again, the schedule is drawn on the assumption that this mode of operation will prevail throughout the program.

The schedule as drawn indicates that the testing of the U-25 channel equipment in the Soviet facility will begin on 15 June 1976.* The length of the U.S.S.R. test program has been left open as it is considered to be unwise to attempt at this time to judge what test duration will be required. For preliminary planning and budgeting purposes, however, it is felt that a duration of at least twelve months should be considered. It is further believed that should the two channel option be adopted, that it will not perturb the master schedule initial test start date in the Soviet facility of 15 June 1976.

4.2 U-25 Channel Master Schedule

The master schedule for the U-25 program is illustrated in Fig. 4-1 (Drawing No. U-25-1304). This master schedule was drawn up based upon assumptions that:

- A. The detail design of the channel will start no later than 1 December 1974.
- B. The schedule would include a three month test period in the High Performance Demonstration Facility (HPDF) located at the Arnold Engineering Development Center (AEDC).
- C. The modification of the AEDC facility for testing the U-25 channel will begin in a time frame which will insure completion on time to support scheduled test start date.
- D. The required modifications at AEDC will include fabrication of a new low pressure combustion chamber.
- E. The required modifications at AEDC will provide a capability for injection of electrode maintenance materials.
- F. The required modifications at AEDC will include the continuous room temperature water cooling option for the HPDE magnet.

A critical feature to be noted on the Master Schedule and Design Schedule, Figs. 4-1 and 4-2, is the concurrency feature. The schedules have been coordinated in such a manner that material procurement and fabrication can begin in parallel with design as soon as the necessary definition of components is completed.

*Since Final Design of the U-25 channel system did not commence on 1 December 1974, all schedules in this section should be transposed in time to reflect the actual commencement of Final Design.

U-25 CHANNEL
MASTER SCHEDULE

Fig. 4-1. U-25 Channel Master Schedule

Fig. 4-2 U-25 Channel Final Design Schedule

4.2.1 Channel Testing at AEDC. If all of the modifications discussed in Paragraph 3.2 are accomplished in a timely manner, the AEDC High Performance Demonstration Facility can support test run durations of the U-25 channel for periods of approximately thirty (30) minutes to one (1) hour. Longer duration test run times at AEDC will require further modification in order to provide liquid oxygen (LOX) storage. It would also require a vaporizer to convert the LOX from a liquid to a gaseous state. It is our understanding that the details of the modifications required to accomplish compatibility with the U-25 requirements have been transmitted to OCR by AEDC. The major additional modification would appear to be the new combustion chamber to be designed for the relatively low operating pressure required by the U-25 system.

Testing of the U-25 channel at AEDC is a highly desirable feature of the program as it will enable certain "lessons learned" to be incorporated into the system in the form of equipment changes or operational procedure changes prior to test operation in the U.S.S.R. Although no detailed statistics exist, our past experience with MHD generators would indicate that data showing the number of forced shutdowns versus maximum operation duration achieved for an MHD channel would resemble the curve shown in Fig. 4-3.

Fig. 4-3. Number of Forced Shutdowns vs Operating Duration Achieved

As may be seen in Fig. 4-3, it is expected that a large number of early forced shutdowns may be encountered in the shakedown phase of the test. It is then anticipated that a relatively easy extension of operating duration may be achieved to a point where a different class of problems is encountered. Further, we believe that it is likely that a significant break in the curve will probably occur

when operating duration of the order of one (1) hour is achieved. This belief is based upon likelihood that the time required to properly slag the channel can be reduced to approximately one (1) hour by heavy injection of the electrode maintenance material.

4.2.1.1 Limitation of AEDC Test Scope. The AEDC magnet is capable of producing a steady field of up to four (4) Tesla. Since this is the case, the test conditions capable of being produced at AEDC offer a much wider spectrum of operating possibilities than those which will be encountered at the U-25 facility, in spite of the fact that the test duration in AEDC is limited. It cannot be over-emphasized that the test objectives at AEDC must be very limited in order to limit the time consumed by the AEDC test. There is little doubt that the temptation to conduct "just one more test" must be severely restrained, and that the decision to remove the channel from the AEDC facility for shipment will be one of the most difficult decisions of the program. It is our opinion that it will be necessary to effect this removal before all problems have been ironed out. The purpose of this section, then, is to define the test objectives at AEDC. It is hoped that by clearly defining these objectives, their scope may be limited.

In light of the foregoing discussions, therefore, it is recommended that the test objectives at AEDC should be limited to:

- A. Demonstration of the integrity of the cooling system of the U-25 channel.
- B. Preliminary operation of the channel at field strengths of 2.2 Tesla and below.

NOTE: Since the likelihood of damage to the channel will be greatly magnified at the higher electric fields which would be produced at higher field strengths, they should not be attempted prior to shipment to the U. S. S. R. if only one channel is provided.

- C. Establishment of the time required and the proper feed rates of electrode maintenance materials to properly slag the U-25 equipment.

NOTE: It cannot be assured a priori that the operating duration at AEDC will be adequate to completely slag the channel.

- D. Demonstration of the hot side integrity of the electrode surfaces.

It is believed that if the test objectives can be limited to the above factors that the three month test program at AEDC is realistic.

4.3 U-25 Final Design Schedule. Figure 4-2 (Drawing No. U-25-1306) depicts the final design schedule for the U-25 MHD Channel System. Several features of the master schedule are duplicated here, however they have been expanded to include more detail. For this reason, they will be discussed here rather than with the master schedule. It might be well to note that on this schedule, as well as the master schedule, concurrency of design, procurement and fabrication is featured throughout.

In addition to the detailed preparation of drawings for the fabrication of the channel, the final design phase of the program must include:

- A. Design, fabrication and test of an electrode maintenance test channel.
- B. Definition of test plans for AEDC and the U-25 facilities, and updating of the U-25 test plan based on AEDC experience.
- C. The design, fabrication and test of a model channel variable wall angle section.
- D. Development of field computer programs and data logging systems which will be used when the equipment is being operated in Moscow.

The final release of drawings is scheduled for 6/15/75 and should permit the channel to be completed on 12/15/75, assuming concurrency.

4.4 Two Channel Option. The Master Schedule discussed in Paragraph 4.2 above was prepared on the basis of fabrication of a single channel with a pre-shipment test period of three months at the Arnold Engineering Development Center prior to shipment and test at the Soviet U-25 facility. As we have seen, the test objectives at AEDC must be severely limited in order to limit the test program to three months. MEPPSCO recommends that it would be cost effective for OCR to consider the fabrication of two identical channels one of which would be committed to a lengthy test program at the Arnold Engineering Development Center while the second would be committed to the test program at the Soviet Union. The scheduled completion of assembly of the AEDC channel would be shown on the Master Schedule; the scheduled completion date of the channel for the U-25 installation would be 5/15/76, that is to say almost five months after completion of the Number 1 channel. The second channel would be able to benefit from the AEDC experience during the final fabrication program and modifications indicated by the test program could be incorporated in the final fabrication process. Thus the initial phase of testing of the first channel at AEDC would be essentially proof testing of the channel for the U-25 under modest electric field operating conditions, and the proof testing results could be incorporated in the channel for the U-25. Following shipment of the second channel to the Soviet Union, the first channel would remain at the AEDC facility and could be utilized for high field strength testing for periods of approximately one hour.

With the high field strength available at the AEDC magnet, 4 Tesla in continuous operation, the performance of the windowframe channel will be much improved over that which could be achieved in the U-25 installation. Even more important, the stresses that the channel would need to withstand would be increased and would approach those realistically obtained in a full scale power plant. Most notable is the axial electric field strength which could be achieved. While the channel in the U-25 will display a maximum interframe voltage of approximately 15 Volts, at AEDC this voltage could be increased to levels as high as 40 Volts per frame. This level will provide a realistic examination of the electric field withstand capability of the windowframe channel.

An additional feature of the high field strength test of the equipment would be the near simulation of the after portions of a full scale MHD power plant generator which will be achieved. In order to achieve the appropriate pressure ratio with the channel at AEDC and at 4 Tesla, it will be necessary to reduce the conductivity levels to approach those that would be achieved in a base load power plant, that is to say of the order of 2-3 Mhos per meter. This reduction can be achieved by reduced oxygen enrichment as well as by reduction of seed level. When this is done, the conductivity variation throughout the generator should approach that of the rear portions of a real full scale power plant. This is indicated in Fig. 4-4, where the conductivity variations through a number of generators of different size is given. The portion of the generator that would be covered by the U-25 equipment in the AEDC facility is indicated.

4.5 Field Support Personnel

4.5.1 Field Support Organization. Figure 4-5 depicts the tentative U-25 Field Organization required for operation at the U-25 facility. It is anticipated that seventeen field personnel will be involved in the U-25 field operations in the Soviet Union.

The Field Organization Chart also shows the important places where the U. S. field organization would interface with the Soviet Staff of the U-25.

The overall program will be headed by a U-25 Program Field Director reporting directly to the Office of Coal Research. Personnel reporting to the program field director will be divided into two separate operating groups:

- A. Engineering
- B. Technical/Scientific.

Fig. 4-4 Conductivity versus Temperature and Conductivity Variation Through Different Sized Generators

Fig. 4-5.

U-25 FIELD ORGANIZATION CHART
17 PEOPLE

The Engineering Section will be directed in its efforts by an Engineering Field Director. This section, in addition to the director, will consist of a mechanical engineer, draftsman, machinist, lead mechanical technician and two mechanical technicians. Also in this section there will be an instrumentation engineer and an instrumentation technician. Additionally, the section will also include a supervising test engineer and a test engineer. The engineering field section will be responsible for assembly, maintenance, and modification of the hardware and all of its related instrumentation. The section will also be responsible for routine coordination of test conduct through the efforts of its test engineers.

The Technical/Scientific Section will be directed in its efforts by a Technical/Scientific Director. This section, in addition to the director, will be staffed by a gasdynamicist, engineer-programmer, and an engineering assistant. The technical/scientific section will be responsible for definition of all parameters of the test program. They will also be responsible for all field data analysis and all of the related scientific aspects of the program.

During around-the-clock testing, the organization can be modified as shown in Fig. 4-6 to provide an engineer and technician for continuous duty to interface with the Soviet operating personnel.

4.5.2 Personnel Recruiting and Selection. Since it is anticipated that the test program in the Soviet Union will be lengthy, on the order of 12 to 18 months or longer, the recruiting and selection of field personnel must be very carefully considered. Personnel operating at such a great distance from the "home office" in a foreign country must be exceptionally well qualified in their chosen field. They must be capable of operating "on their own" with a bare minimum of direction, and should be capable of adopting procedures and fixes that they might not be called upon to accomplish in a domestic environment.

4.5.3 Personnel Logistics. It would appear from a personnel logistics standpoint that two approaches are available for handling the field personnel. These approaches are:

- A. Allow field personnel's dependents to accompany them and remain at the test site for the duration of the test.
- B. Allow no dependents to accompany the field personnel and provide for rotation and relief.

If the elective of having dependents accompany all field personnel is chosen, some of the more obvious aspects to be considered would be:

Fig. 4-6. U-25 FIELD ORGANIZATION CHART
MODIFICATION FOR AROUND THE CLOCK TEST

- A. Availability of adequate family housing.
- B. Availability of dependent schools.
- C. Availability of shopping facilities for dependents who probably will not speak or understand Russian.
- D. The logistics involved in moving families and their possessions to Moscow and return.

Of the aspects considered here, the major one could well be the availability of family housing.

If the elective of not having dependents accompany field personnel is chosen, some of the more obvious aspects to be considered would be:

- A. Personnel could be quartered in bachelor quarters.
- B. Relief personnel must be included in the program to allow scheduled (or possibly on occasion unscheduled) rotation of personnel to the U.S.
- C. Cost effectiveness of frequent rotation of field personnel.
- D. Possible degradation of test results due to frequent shifting of personnel.

One of the more desirable features of this approach would be the ready availability of personnel at one location in the event that rapid repairs or modification to equipment were required. The major undesirable feature could well be the additional field personnel required, plus the potential for high travel costs.

Regardless of the approach taken to providing personnel logistic support, it is strongly recommended that these matters be coordinated with the Soviets at a very early date. Recruiting of very highly qualified personnel can only proceed after very definitive decisions have been made relative to their logistic support and specific ground rules have been established.

4.6 Field Support Facilities

The field support facilities required for the U-25 scheduled test in the Soviet installation will consist of a channel assembly and maintenance area, an office area and data logging and computational facilities. Each of these support areas will be discussed individually in Paragraphs 4.6.1 through 4.6.3 below.

4.6.1 Channel Assembly and Maintenance Area. It is contemplated that a room approximately 30 feet wide by 60 feet long, or 1800 square feet (166.5 square meters) will be required to accommodate the channel assembly and maintenance functions. Figure 4-7 (Drawing No. U25-1309) indicates an economical utilization of space and further indicates that a minimum ten (10) foot wide door should be provided to allow easy removal of the completely assembled channel. A study of this sketch indicates some of the support areas required to make the assembly and maintenance areas functional. The assembly area is divided into two functional areas even though no partitions exist. The first area is the sub-assembly area where sections of the channel may be assembled. The other area will be utilized to assemble the total channel including the nozzle and diffuser sections. From this full assembly area, the channel may be readily moved to the magnet area. An instrument test area is included to provide for calibration and checkout of channel instrumentation. The welding and brazing area will be used to fabricate or repair windowframes or other items of that nature. The materials and stock area will contain spare parts and maintenance items for the channel. It is also anticipated that certain maintenance machine tools, i. e., grinder, drill press, lathes, milling machine, band saw, etc., will be included in the facility. It is also expected that the four technicians shown on the field organization chart will be based in the assembly and maintenance area.

4.6.2 Office Area. It is anticipated that the thirteen (13) remaining field personnel will be based in an office area that will be provided by the Soviets. This office would preferably be located in close proximity to the assembly and maintenance area. In addition to the usual desks, file cabinets, etc., the office area should contain:

- A. Two drafting tables with drafting machines.
- B. A drawing file which would include one complete set of "as built" vellums upon which modifications to the channel could be entered. The drawings should be in both English and metric units with all call-outs in English and Russian.
- C. A blueprint machine for reproducing the vellums.
- D. A reproduction machine of the Xerox-type.
- E. A desk calculator (preferably one which would include a plotter).

4.6.3 Instrumentation and Computational Requirements. One of the most important aspects of the U-25 final design will be the definition of the instrumentation requirements and the means by which the data will be gathered, logged, stored and analyzed. In addition, computation facilities will be required for on

Fig. 4-7. U-25 Fabrication and Assembly Area

the spot analyses of the test results and modifications of the test plans based upon up-to-date test results. These would use programs developed during the final design phase. In addition, all computations of interest cannot be anticipated. It is to be expected that some field program development will be required. There are two options that might be exercised for achieving this capability. They are:

- A. Utilization of Soviet computation and data logging facilities.
- B. Provision of a mini-computer based data logging and/or computing capability exclusively for U.S. operation. This unit might conceivably be interfaced directly in real time to the Soviet data logging facility.

The option of utilizing Soviet facilities would require that the real time instrumentation be compatible with the Soviet data logging facilities, while off line computer programs for analysis be written for the Soviet system. It is not known at this time what the extent of difficulty would be in accomplishing this, but it is believed that it will be substantial and, moreover, will require considerable time and effort for checkout in the field. Therefore, MEPPSCO recommends that OCR elect the option of providing self-contained mini-computer based data logging and field computation equipment as part of the U-25 program. This equipment could be thoroughly checked out and debugged during the test period at AEDC. Then in Moscow it would only be necessary to plug-in and get on stream.

It is our understanding that Westinghouse has also opted for complete U.S. data logging capability with approximately 100 channels in connection with the U-02 experiments to be conducted with U.S. electrode development channel as a part of the cooperative MHD program. The U-25 equipment would be similar but more extensive, but would also provide capability for off-line analysis and program development. It is felt that this additional capability is required in view of what is likely to be a lengthy and detailed test program.

In order to obtain a representative layout of the data logging and computation equipment, as well as obtain figures for the program cost estimate, representatives of the Digital Equipment Corporation (DEC) were contacted and invited to prepare a block diagram and quotation. The following assumptions were utilized:

- A. The choice and cost of various transducers is not influenced by the use of a computer based data logging system.
- B. To as much of an extent as possible, the computer hardware will be supplied by a single manufacturer with support facilities in Europe which can be utilized, and equipment presently supplied to the Soviet

Union. A support sub-contract would be awarded to the most convenient supporting activity of this manufacturer. It is felt that turnkey is the only feasible approach considering the U.S.S.R. test site.

C. The capabilities which are desired are:

1. CPU + 32K x 16 bit and priority interrupt
2. Real time clock
3. Teletype (30/sec)
4. Dual disk drive, 2.4×10^6 word storage
5. Tape drive (data to be logged on disc and transferred to tape off line for transmission to U.S.)
6. Digital input/output
7. Plotter control and plotter
8. 256 channel Analog-Digital Converter and controller (separate supplier).

A block diagram of the system proposed by DEC is given in Fig. 4-8. The DEC proposal is included as Appendix 4. The equipment would normally be boxed in four (4) racks, but if desired the number of racks could be reduced to two (2). In addition, the TTY, printer and plotter are free standing. This equipment should be housed in the U-25 control room with provision for portability to the office area. Software development for this system is included in the program plan. A real time FORTRAN designed for industrial monitoring would be used and would simplify software development.

Three functions for the instrumentation system can be identified:

- A. Data logging and monitoring for U.S. supplied equipment.
- B. Data logging for U-25 status and special Soviet experiments, i.e., conductivity probe.
- C. System protection and alarm.

4-8. Block Diagram of Computation Capability

It is assumed that all system adjustment except alarm and protection will be done manually separately from the instrumentation.

1. U.S. equipment: With the U.S. equipment, the entire instrument channel is U.S. responsibility. Data logging could include, but not be limited to:

<u>Function</u>	<u>No. of Channels</u>
STATIC PRESSURE	
Nozzle	4
Diffuser	6
Channel	
Centerline	24
Transverse (5 places x 4 taps)	20
CURRENT	
Channel (split frame)(isolated)	24 (12 x 2 adjacent)
Power takeoff distribution (hold isolated)	10
Output	1
Potential and potential difference (isolated)	45
Temperature (isolated)	14
COOLING WATER	
Temperature	18
Flow Rate	18
Pressure	18
TOTAL ANALOG CHANNELS	202

2. U-25 Status: For these inputs, interface with the U-25 transducers is required:

- Fuel flow
- Oxidizer flow
- Air flow
- Oxygen Flow
- Seed flow
- Maintenance flow (2)
- Preheat temperature (at combustion chamber)
- Combustion pressure
- Combustion fluctuations (rms)

Burner coolant flow	
Burner coolant exit temperature	
Magnet current (or field)	
Plasma temperature (if provided)	
Conductivity (if provided)	
Total water coolant flow overall bulk rise	
Inverter status (3)	
Total coolant flow	
Total analog channels	20

The 256 channel systems provide some margin for the above needs; no doubt the margin will be used up.

3. Protection and Alarm: Protection and alarm involving the U-25 facility and not the U.S. equipment directly are and should be under the control of the facility operator.

Protection and alarm involving the U.S. equipment will require transmission of information to the U-25 operator and/or equipment. This information transfer can be oral, visual or automatic as the particular case requires. The automatic transfer requires interface with the U-25 facility.

Although there are exceptions, in the case of an MHD generator, response to an alarm generally involves rapid shutdown of the combustion equipment. It is presumed that the U-25 is already equipped for this function. Thus, it will be necessary to provide reliable, redundant tie in to the Soviet system in order to assure protection. This tie in should not rely on the computer; all alarm functions utilizing regular instrumentation should provide the alarm signal independent of the data logging function.

In addition to the above instrumentation, various signals should be displayed in the control room including:

- U-25 status
- Static pressure distribution (manometer board or "Metrascope")
- Channel voltage distribution ("Metrascope")
- Channel current distribution ("Metrascope")
- Coolant system data
- Output parameters

Finally, the system includes provision for input/output of digital data (switch or valve position, etc.).

It is to be noted that, should OCR elect to utilize the Soviet data logging system, the channels suggested above are entirely compatible with that system as described in the Soviet specifications.

SECTION V
COST ESTIMATE

5.0 COST ESTIMATE

5.1 General Information

The cost estimate and back-up data for conduct of the final design, fabrication and testing of the U-25 channel system have been provided to OCR under separate cover.

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APPENDIX 1

USSR-US CORRESPONDENCE ON U-25 CHANNEL

• SUGGESTED EXCEPTIONS TO SOVIET U-25 SPECIFICATIONS •

• REQUESTED CLARIFYING PHOTOGRAPHS •

• DRAWING CLARIFICATIONS •

September 1974

• SUGGESTED EXCEPTIONS TO SOVIET U-25 SPECIFICATIONS •

1. Coolant Water Flow

Assuming rough walls, the channel wall at 1940°K and cold walls for diffuser and nozzle the water flow provided by the Soviets (560 mt/hr) is adequate. However, prudence requires that the water side on the channel shall be capable of handling cold wall rates in case of failure to slag the channel properly or loss of the slag layer during operation for any reason.

To achieve full cold, rough wall capability, the water coolant flow should be increased 25% to 700 mt/hr.

2. Water Manifolding

To facilitate interfacing and flow control to the various US components, it is suggested that the interface be modified as per the attached sketch.

3. After Lateral Retaining Forks

It is suggested that the after lateral retaining forks be remounted on the pole face by match drilling during installation of the US channel as per the attached sketch.

4. Circulating Water:

The Soviet interface data mentions a high dew point in the magnet aperture. During periods when the channel is installed in the magnet, but not being operated, it is suggested that demineralized water at a temperature above the highest dew point to be expected shall be circulated through the components to avoid condensation. This required flow should not be more than ten (10) tons/hour.

The external parts of the US channel and nozzle are "hot" electrically. To isolate the channel from the pole faces, the poles should be covered with $1/8''$ thick glass reinforced, silicone bonded sheet (NEMA G-7 or equivalent).

•SUGGESTED PHOTOGRAPHS TO ASSIST INTERFACE•
•INTERPRETATION•

- a) Diffuser Interface Flange
- b) Nozzle (US) - Combustion Chamber Interface Flange
- c) Channel to Magnet Pole Attachments
- d) Details of Method of Compensating for Misalignment of Mating Flanges
- e) Showing Magnet in Opened Position so as to Avoid Interference With Mounted Components During Installation

• DRAWING CLARIFICATIONS •

- a) Are the attached interpretations of PUC 12 correct?
- b) On Page 23, please explain function of indicated holes on magnet face.

ХЕМА,

дополняющая рис. исходных тнж
конструирования канала-МГД-ген

Установки У-25

Рис. 12

ARROW POINTING
TO WRONG HOLE

Вид В
М 1:20

1.045

56 отб. $\Phi 28A5$

62.5
SHOULD BE
60.0

STEEL
FLA
ПЛАНЫ

По контуру от 51 контуру

М 1:5

55 ± 0.165
3 ± 0.118

56 отб. $\Phi 28A5$

3 ± 1

45 ± 1
1.771

PUC Nº. 23

$\frac{1}{8}'' = 1''$

PUPA

PROPOSED SUPPORT LOCATION

9-4-74 U-25 - 1301

A1-8

TOLERANCES (EXCEPT AS NOTED)		MEPPSCO, INC.	
DECIMAL		SCALE	DRAWN BY EJ HUNT
FRACTIONAL			APPROVED BY
TITLE	MODIFICATION TO SOV. PIPING		
DATE	9-74	DRAWING NUMBER	U 25-1298

О Т В Е Т Ы

на вопросы к советской документации по У-25, заданные
фирмой "Менпско"

1. Насосное оборудование системы охлаждения канала МГДГ Установки У-25 может обеспечить расход воды 680^{TH} /час при давлении на входе в канал 40 ата с температурой воды 40°C .

Однако использование этого резерва является нежелательным и должно быть хорошо аргументировано американской стороной.

2. Предлагаемая на рис. - 25 - I298 модификация не позволяет использовать имеющиеся трубопроводы.

Осуществление этого предложения возможно при условии подсоединения к нижним фланцам коллекторов новых трубопроводов по предлагаемой схеме (см.рис. № I). Учитывая, что эти трубопроводы пригодны только для американского канала, они должны входить в комплект поставки.

Обращаем Ваше внимание, что на этих трубопроводах должны быть размещены расходомерные устройства.

3. На задней плоскости полюса магнита имеются накладки для крепления советских каналов. Желательно установку опор для американского канала производить с использованием имеющихся мест крепления. Расположения мест крепления см. Рис. № 2.

Сверловку американских опор желательно произвести при монтаже канала.

4. Утверждение, что советской стороной задано высокое значение точки росы в объеме магнита, неточно.

Точка росы (80°C) может быть только внутри канала при работающей камере сгорания.

При неработающей Установке влажность внутри канала и вне его соответствует атмосферной.

Поэтому для предотвращения конденсации влаги на элементах конструкции канала, установленного в магните, вполне достаточной подогрев охлаждающей воды до $60 + 70^{\circ}\text{C}$. Подобный режим можно обеспечить работой одного насоса (расход $300 \text{ м}^3/\text{час}$) при включенных теплообменниках по технической воде.

5. Электроизоляцию полюсов магнита от корпуса канала выполнить возможно при условии поставки американской сто оной не бходимых материалов.

Чертежи электроизоляции должны быть согласованы с советской стороной.

6. Все основные данные по компенсирующим возможностям контура У-25 и в частности требования к непараллельности и неплоскостности фланцев канала указаны в ранее переданной американской стороне схеме, дополняющей Рис. I "Исходных данных для конструирования канала МГД-генератора Установки У-24"...."

Американский канал должен отвечать этим требованиям. Дополнительно сообщаем, что поперечное смещение фланца канала относительно фланца диффузора парогенератора на величину не более $\pm 10 \text{ мм}$ может быть скомпенсировано путем деформации тороидного компенсатора парогенератора.

Поворот выходного фланца канала в пределах $\pm 15 \text{ мм}$ может быть скомпенсирован путем организации овальных отверстий на круглом фланце диффузора парогенератора. Аналогичным путем может быть скомпенсирован поворот

входного фланца канала относительно сопловой части камеры сгорания.

Допустимая величина смещения ± 10 мм.

Для увеличения свободы компенсации следует предусмотреть возможность перемещения канала в поперечной плоскости в объеме магнита при монтаже.

7. К вопросу о правильности размеров на рис. 12:

размер 62,5 неправилен, должно быть 60 мм;

положение стрелки на размере 875 ± 1 должно заканчиваться на линии, проходящей по оси последнего отверстия по горизонтали.

8. К вопросу о назначении отверстий на рис. 23:

указанные отверстия служат для крепления грузозахватных устройств и используются только при транспортировке нижнего полюса магнита

Answers to the Questions on Soviet Documentation of U-25 Requested by MEPPSCO

1. The pumping equipment of the channel cooling system of the MHD installation U-25 can supply 680 t/hr with the pressure at the canal entrance of 40 atm and temperature of water 40^o C. However it is undesirable to use this reserve and the arguments in support of it should be well founded.
2. The proposed modification illustrated on the drawing 25-1298 does not allow to utilize existing piping. Realization of this proposal is possible if new piping is attached to the lower flanges of the collectors according to the attached drawing (See Drawing No. 1). Since this piping will be utilized only for the American canal, it must be supplied with the installation.
3. On the back plane of the magnet's pole there are "bosses" for fastening of Soviet canals. It is desirable to utilize these existing locations for fastening the American canal when the installation is made. The location of these "places of fastening" are shown on Drawing No. 2. The drilling of American flanges should be made during the mounting of the canal.
4. The statement that the Soviet side assigned a high value for the dew point within the magnet is inaccurate. The dew point (80^oC) can exist only inside the canal when the combustion chamber is operating. When the installation is not operating the humidity inside and outside the canal is that of the atmosphere. Therefore to prevent the condensation of moisture on the construction parts of the canal installed inside the magnet, it is sufficient to heat the cooling water to 60-70^oC. This can be done with the help of one pump (300 cu m/ hour) when the heat exchangers of technical water are plugged in.

5. The electrical insulation between the magnet's poles and the body of the canal could be done if the American side supplies the necessary materials. The drawing of the electrical insulation should be coordinated with the Soviet side.
6. All basic data on the compensating ability of the contour U-25 and in particular the requirement of "parallelism" and "flatness" of flanges of the canal are shown on the drawing previously delivered to the American side, which supplement drawing 1, "The basic data for construction of MHD generator at U-25 installation". The American canal must satisfy these requirements. In addition we can inform you that a cross-displacement of not more than ± 10 mm of the canal flange with respect to the flange of the steam generator diffuser can be compensated for by the deformation of the steam generator's toroidal compensator. Similarly, the twist of the entrance flange of the canal with respect to the nozzle part of the combustion chamber can be compensated for. Let us assume that the displacement is ± 10 mm. In order to increase the freedom of compensation it is necessary to take into account a possibility of displacement of the canal in the cross plane within the magnet during the installation.
7. On the subject of the correction of the dimensions on Drawing 12: Dimension 62.5 is incorrect; must be 60 mm. The position of the arrow showing dimension 875 ± 1 must end on the line passing along the axis of the last opening along the horizontal.
8. On the subject of the purpose of openings on Drawing 23: The shown openings serve for fastening the lifting devices and are used only during the transporting of the lower pole of the magnet.

Reply to October 22, 1974 Answers Provided by the Soviet Side
on October 15, 1974 to "Exceptions and Clarifications
to Soviet U-25 Specifications" September 6, 1974

The numbers referred to answers provided to the questions on specification submitted by the U.S. side on 15 October 1974.

1. The U.S. equipment will be designed for a maximum cooling water flow of 680 t/hr at 40 atm. Should initial operation of the channel show that this much flow is not required when potential loss of the slag layer is considered, the flow can be reduced through use of the throttle valves which will be provided with the U.S. equipment.
2. The solution proposed by the Soviet Side is acceptable and the new piping will be provided by the American side (See Drawing U-25-1298, Rev. A, attached).
3. The "bosses" on the back plate of the magnet pole will be utilized for lateral support of the American channel. Thrust takeoff will be at the front plane of the magnet pole.
4. Clarification provided by the Soviet side is understood. Use of cooling water at 60-70°C is adequate. The required flow rate during idle periods is much less than 300 cu m/hr, say 10-20 cu m/hr.

QUESTION: Is the capability to heat the idling cooling water flow to 60-70°C presently available?

5. The insulating material between the magnet poles and the body of the channel will be provided by the American side and the installation will be coordinated with the Soviet side.
6. The American channel will satisfy the requirements supplied by the Soviet side and the American side takes note of the capability for correction of cross-displacement of the diffuser flange and twist of the channel entrance flange. It was these latter points with which we were concerned.
7. Acknowledged.
8. Acknowledged.

VIEW A-A

A1-15

VIEW B-B

9/7/74	A	REVISED & REDRAWN
DATE	LETT	DESCRIPTION
		REVISION

REVISED, ETC.	
PUPA	
MODIFICATION TO SOV. PIPING	
10-17-74 U-25-1298

United States Department of the Interior

OFFICE OF COAL RESEARCH
WASHINGTON, D.C. 20240

October 22, 1974

AIR MAIL

Professor A. E. Sheindlin
High Temperature Institute
Moscow

Dear Professor Sheindlin:

Following the discussions on the preliminary designs of the U.S. channel to be installed in the U-25 facility, the U.S. side would like the Soviet side to confirm that the following specifications can be achieved by the U-25 pilot plant at the time of installation of the U.S. channel.

I. Basic Thermodynamic Parameters.

1. Oxidant mass flow up to 49 kg/sec.
2. Rate of oxygen enrichment up to 42 percent by weight.
3. Fuel: natural gas as per Soviet specifications with a mass flow up to 5.8 kg/sec.
4. Oxidant preheat temperature up to 1200-1250° C.
5. Combustion chamber heat losses about 4 percent.
6. Stagnation pressure in the combustion chamber: 3.2 atm.
7. Outlet stagnation pressure at the inlet to the steam generator: 1 ± 0.02 atm abs.
8. The steam generator is rated for continuous operation without load on the MHD generator under the operating conditions described above.
9. Potassium is the seed.
10. Starting and stopping times of combustion chamber are 20 minutes.
11. The operation of the combustion chamber is stable in the range described above and the average conductivity at the combustion chamber outlet remains constant in the range of 40 kg/sec. - 55 kg/sec. at the maximum pressure.

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II. Cooling Parameters.

1. Water cooling mass flow: up to 680 t/hour.
2. Inlet pressure to the cooling system is at least 40 akm abs.

Other parameters are unchanged and described in "Reference data for construction of MHD generator duct of U-25 plant according to the program of cooperation between US and USSR on MHD" dated 1973.

William D. Jackson
MHD Program Manager

APPENDIX 2

U-25 DESIGN PARAMETERS

APPENDIX 2

Table App.2-1	Detailed Specification for U-25 Revision 6 Gas Side Loft
Table App.2-2	Design Calculations
Table App.2-3	Polynomial Fit to Channel Dimensions

TABLE APP. 2-1
DETAILED SPECIFICATION FOR U-25 REVISION 6 GAS SIDE LOFT

X	D1	D2	PHI *	B
0.	.33110	.73300	-----*	1.243
.10	.33267	.73000	-----*	1.331
.15	.33361	.73000	-.4099	1.450
.20	.33456	.73000	-.4416	1.519
.30	.33631	.73000	-.5049	1.657
.40	.33944	.73000	-.5682	1.795
.50	.34250	.73000	-.6315	1.933
.60	.34724	.73000	-.6943	2.071
.70	.35207	.73000	-.7531	2.209
.80	.35639	.73000	-.8214	2.209
.85	.35930	.73000	-.8530	2.209
.95	.36410	.73000	-.9163	2.209
1.05	.36837	.73000	-.9796	2.209
1.15	.37359	.73000	-1.0430	2.209
1.25	.37827	.73000	-1.1063	2.209
1.35	.38238	.73000	-1.1696	2.209
1.40	.38593	.73000	-1.2000	2.209
1.50	.38806	.73400	-1.1844	2.209
1.60	.39017	.73970	-1.1639	2.209
1.70	.39230	.74470	-1.1533	2.209
1.80	.39446	.74980	-1.1373	2.209
1.90	.39666	.75500	-1.1222	2.209
2.00	.39883	.76030	-1.1067	2.209
2.10	.40115	.76570	-1.0911	2.209
2.20	.40343	.77120	-1.0756	2.209
2.30	.40603	.77640	-1.0600	2.209
2.40	.40862	.78180	-1.0444	2.209
2.50	.41126	.78730	-1.0289	2.209
2.60	.41395	.79290	-1.0133	2.209
2.70	.41669	.79860	-.9973	2.209
2.80	.41949	.80450	-.9822	2.209
2.90	.42234	.81050	-.9667	2.209
3.00	.42525	.81660	-.9511	2.209
3.10	.42824	.82280	-.9355	2.209
3.20	.43163	.82360	-.9200	2.209
3.30	.43521	.83420	-.9044	2.209
3.40	.43835	.84000	-.8889	2.209
3.50	.44253	.84600	-.8733	2.209
3.60	.44640	.85210	-.8573	2.209
3.70	.45031	.85830	-.8422	2.209
3.80	.45433	.86480	-.8267	2.209
3.90	.45844	.87140	-.8111	2.209
4.00	.46267	.87320	-.7955	2.209
4.10	.46736	.88450	-.7800	2.209
4.20	.47219	.89110	-.7644	2.209
4.30	.47715	.89790	-.7489	2.209

*The first frame intersects the axis at $x=.149$ meters and has a non-zero PHI, thus for $x < .149$ PHI is undefined.

X	D1	D2	PHI	B
4.40	.43224	.90490	-.6303	2.209
4.50	.43749	.91210	-.7173	2.209
4.60	.49233	.91950	-.7022	2.209
4.70	.49343	.92720	-.6367	2.209
4.80	.50414	.93520	-.6711	2.209
4.90	.51010	.94320	-.6555	2.209
5.00	.51671	.95070	-.6400	2.209
5.10	.52354	.95340	-.6244	2.209
5.20	.53059	.96640	-.6089	2.209
5.30	.53739	.97470	-.5933	2.209
5.40	.54556	.93320	-.5773	2.209
5.50	.55367	.99170	-.5622	2.209
5.60	.56203	1.00070	-.5466	2.209
5.70	.57079	1.01000	-.5311	2.209
5.80	.57932	1.01930	-.5155	2.209
5.90	.58952	1.02960	-.5000	2.209
6.00	.59538	1.04340	-.4524	2.061
6.10	.60260	1.05630	-.4048	1.923
6.20	.60869	1.07030	-.3571	1.735
6.25	.61134	1.07700	-.3333	1.716
6.30	.61196	1.08400	-.3095	1.647
6.40	.61319	1.09700	-.2619	1.509
6.50	.61440	1.11110	-.2143	1.371
6.60	.61567	1.12400	-.1667	1.233
6.70	.61691	1.13700	-.1190	1.095
6.80	.61814	1.15100	-.0714	.957
6.90	.61933	1.16400	-.0233	.819
6.95	.62000	1.17100	0.	.750

$$.149 \leq x \leq 1.4$$

$$\text{PHI}(X) = -.315 - .633 X$$

$$1.4 < x < 5.9$$

$$\text{PHI}(X) = -1.2 + .15556(X-1.4)$$

$$5.9 \leq x \leq 6.95$$

$$\text{PHI}(X) = .47619 (X-6.95)$$

TABLE APP. 2-2
DESIGN CALCULATIONS

.55	0.1	6.25	0.9	.622	0.0	1.0	100.00	-.00375				
1.0	.0025	.00065	0.5	.006276	.002133	0.0	1.236	50.00				
58.37	1.933	0.0	0.0	.350	2734							
1	1	1	0	1	1	2	1	0	0	3	1	1
0.1	1.133	.0000	.0000	.0093								
-1.20	0.0000	0.0	0.0	.5000	0.0000	.0000	0.0000	000.00				

X0	DX	XMAX	BSHIFT	F1C	F1CX
.5500E+00	.1000E+00	.6250E+01	.9000E+00	.6220E+00	0.
F2C	VD1	VD2	ELO	AKS	EMU
.1000E+01	.1000E+03	-.3750E-02	.1000E+01	.2500E-02	.6500E-03
HWOH	FRICT	THETA	PREC	CAPHI	MASS
.5000E+00	.6276E-02	.2133E-02	0.	.1236E+01	.5000E+02
ENTHALPY	PRESSURE	VOLTAGE	POWER	ETA	D1
.5387E+02	.1933E+01	0.	0.	.8500E+00	.3448E+00
D2	VELOCITY	DENSITY	AREA	COMPH	
.7300E+00	.9151E+03	.2197E+00	.2517E+00	.7132E+00	.3997E+00
D1C	2*DEL*	D2C	H	PRES.	I
.3417E+00	.3121E-02	.7269E+00	.2463E+06	.2009E+06	.2734E+04

X	D1	D2	V	E _{xx}	JY	JX	ETA	PREC	E	PHI
.55	.3449	.7300	-3.	37.	-11132.	3312.	.02	2.91	44.	-.66
.60	.3472	.7300	-1.	90.	-11032.	3463.	.04	2.39	109.	-.69
.70	.3520	.7300	10.	184.	-10793.	2813.	.09	2.35	231.	-.76
.80	.3568	.7300	31.	264.	-10527.	2227.	.14	2.32	342.	-.82
.85	.3593	.7300	44.	300.	-10331.	1956.	.15	2.30	394.	-.85
.95	.3641	.7300	75.	362.	-10074.	1460.	.19	2.76	491.	-.92
1.05	.3633	.7300	113.	415.	-9754.	1020.	.22	2.73	530.	-.93
1.15	.3735	.7300	156.	458.	-9427.	631.	.25	2.70	662.	-1.04
1.25	.3782	.7300	202.	493.	-9099.	290.	.28	2.67	736.	-1.11
1.35	.3823	.7300	252.	522.	-8773.	-9.	.30	2.64	804.	-1.17

X	D1	D2	V	E _{xx}	JY	JX	ETA	PREC	E	PHI
1.40	.3359	.7300	0.	624.	-8669.	-411.	.36	2.60	974.	-1.20
1.50	.3380	.7343	62.	628.	-8696.	-404.	.35	2.57	973.	-1.18
1.60	.3901	.7397	125.	632.	-8723.	-396.	.35	2.54	972.	-1.17
1.70	.3923	.7447	188.	636.	-8749.	-387.	.35	2.51	971.	-1.15
1.80	.3944	.7498	252.	640.	-8774.	-378.	.35	2.48	970.	-1.14
1.90	.3966	.7550	316.	645.	-8799.	-368.	.34	2.45	969.	-1.12
2.00	.3988	.7603	380.	649.	-8823.	-357.	.34	2.42	969.	-1.11
2.10	.4011	.7657	445.	654.	-8847.	-345.	.34	2.39	968.	-1.09
2.20	.4034	.7712	511.	659.	-8870.	-333.	.33	2.36	967.	-1.08
2.30	.4060	.7764	577.	664.	-8896.	-324.	.33	2.33	967.	-1.06
2.40	.4036	.7818	643.	669.	-8921.	-313.	.33	2.29	968.	-1.04
2.50	.4112	.7873	710.	675.	-8945.	-302.	.33	2.26	968.	-1.03
2.60	.4139	.7929	777.	680.	-8968.	-290.	.32	2.23	968.	-1.01
2.70	.4166	.7936	845.	686.	-8990.	-276.	.32	2.20	969.	-1.00
2.80	.4194	.8045	914.	692.	-9011.	-262.	.32	2.17	969.	-.98
2.90	.4223	.8105	983.	697.	-9031.	-247.	.32	2.14	970.	-.97
3.00	.4252	.8166	1053.	704.	-9050.	-230.	.31	2.11	971.	-.95
3.10	.4282	.8228	1123.	710.	-9068.	-213.	.31	2.08	972.	-.94
3.20	.4316	.8236	1194.	717.	-9094.	-202.	.31	2.05	974.	-.92
3.30	.4352	.8342	1266.	724.	-9120.	-193.	.31	2.02	976.	-.90
3.40	.4383	.8400	1338.	732.	-9147.	-182.	.30	1.99	979.	-.89
3.50	.4425	.8460	1412.	740.	-9172.	-171.	.30	1.96	982.	-.87
3.60	.4454	.8521	1486.	748.	-9196.	-158.	.30	1.93	985.	-.86
3.70	.4503	.8533	1560.	756.	-9219.	-144.	.30	1.89	988.	-.84
3.80	.4543	.8643	1636.	764.	-9239.	-128.	.30	1.86	992.	-.83
3.90	.4584	.8714	1712.	773.	-9259.	-112.	.29	1.83	995.	-.81
4.00	.4626	.8732	1790.	782.	-9276.	-94.	.29	1.80	999.	-.80
4.10	.4673	.8845	1868.	792.	-9301.	-81.	.29	1.77	1004.	-.78
4.20	.4721	.8911	1947.	802.	-9323.	-68.	.29	1.74	1010.	-.76
4.30	.4771	.8979	2027.	813.	-9344.	-53.	.29	1.71	1015.	-.75
4.40	.4822	.9049	2108.	823.	-9362.	-36.	.28	1.67	1021.	-.73
4.50	.4874	.9121	2191.	835.	-9379.	-17.	.28	1.64	1027.	-.72
4.60	.4923	.9195	2274.	846.	-9392.	3.	.28	1.61	1034.	-.70
4.70	.4984	.9272	2359.	858.	-9403.	24.	.28	1.58	1041.	-.69
4.80	.5041	.9352	2445.	871.	-9411.	48.	.28	1.55	1049.	-.67
4.90	.5101	.9432	2532.	884.	-9419.	71.	.27	1.51	1057.	-.66
5.00	.5167	.9507	2620.	898.	-9443.	85.	.27	1.48	1066.	-.64
5.10	.5235	.9534	2710.	913.	-9464.	100.	.27	1.45	1076.	-.62
5.20	.5305	.9664	2801.	929.	-9481.	117.	.27	1.42	1087.	-.61
5.30	.5373	.9747	2894.	945.	-9495.	136.	.27	1.39	1099.	-.59
5.40	.5455	.9832	2989.	962.	-9511.	155.	.26	1.35	1111.	-.58
5.50	.5536	.9917	3085.	980.	-9526.	172.	.26	1.32	1124.	-.56
5.60	.5620	1.0007	3183.	999.	-9538.	192.	.26	1.29	1138.	-.55
5.70	.5707	1.0100	3283.	1019.	-9545.	214.	.26	1.26	1153.	-.53
5.80	.5793	1.0193	3385.	1039.	-9548.	238.	.26	1.22	1169.	-.52
5.90	.5895	1.0296	3488.	1061.	-9558.	258.	.26	1.19	1187.	-.50
6.00	.5953	1.0434	92.	712.	-9283.	765.	.18	1.17	779.	-.45
6.10	.6026	1.0563	156.	432.	-8861.	1301.	.12	1.14	465.	-.40
6.20	.6086	1.0703	192.	135.	-8381.	1812.	.04	1.12	143.	-.35
6.25	.6113	1.0770	199.	-20.	-8121.	2055.	-.01	1.11	-21.	-.33

TABLE App-2-3

Polynomial Expressions for U-25 (Rev. 6) Channel

$D_1(x)$

$$0 \leq X < 6.25$$

$$D_1(x) = \sum_{I=0}^9 A_I X^I$$

COEFS OF D1

=====

$$\begin{aligned} A_0 &= .33141575E+00 \\ A_1 &= .81093420E-02 \\ A_2 &= .17525284E-01 \\ A_3 &= .60160052E-01 \\ A_4 &= -.36553447E-01 \\ A_5 &= .47354949E-01 \end{aligned}$$

$$\begin{aligned} A_6 &= -.13302227E-01 \\ A_7 &= .22003370E-02 \\ A_8 &= -.13383143E-03 \\ A_9 &= .62770682E-05 \end{aligned}$$

$$6.25 \leq X \leq 6.95$$

$$D_1(x) = .6200 + .012371(X - 6.95)$$

$D_2(x)$

$$0 \leq X \leq 1.400$$

$$D_2(x) = 0.7300$$

$$1.4 < X < 6.25$$

$$D_2(x) = \sum_{I=0}^9 B_I X^I$$

COEFS OF D2

=====

$$\begin{aligned} B_0 &= .72866914E+00 \\ B_1 &= .20726219E-01 \\ B_2 &= -.45204236E-01 \\ B_3 &= .11348220E-01 \\ B_4 &= .29101822E-01 \\ B_5 &= -.22457047E-01 \end{aligned}$$

$$\begin{aligned} B_6 &= .72100554E-02 \\ B_7 &= -.12063938E-02 \\ B_8 &= .10359172E-03 \\ B_9 &= -.36114383E-05 \end{aligned}$$

$$6.25 \leq X \leq 6.95$$

$$D_2(x) = 1.171 + .1343(X - 6.95)$$

APPENDIX 3

PERFORMANCE CALCULATIONS BY
STD RESEARCH, INC.

APPENDIX 3

PERFORMANCE CALCULATIONS BY STD RESEARCH, INC.

This Section contains selected material provided by STD Research, Inc.

and includes:

- A. Pertinent excerpts from most recent STD Research, Inc. Progress Report dealing with performance calculations of the MEPPSCO channel (concludes with Fig. 25).
- B. Electrode voltage drop (V_e) as a function of axial station using the same definition of V_e as employed by MEPPSCO. The peak value of V_e in the MEPPSCO calculation was 280 Volts as compared with 380 for the STD calculations.
- C. A voltage current characteristic. It is our understanding that another point at $V = 4000$, $I = 3550$ has been computed ($P = 14.2$ MW) and that for higher currents the flow Mach number will exceed 1.1 in the channel. We have suggested that STD investigate supersonic inlet conditions for the higher currents (lower value of j_y).
- D. Effect of slag layer resistivity on performance
- E. Effect of resistive slag layer on current and Mach number distribution
- F. Typical current and potential distributions

2.4 Design and Off-design Performance of the MEPPSCO U-25 Channel

The input data for the MEPPSCO design of the U-25 SOD channel was modified in Revisions 2, 4 and 5 received by STD on Sept. 5, Oct. 21 and Oct. 25, 1974 respectively (Ref. 1 through 3). Revision 5 was further modified on Oct. 29, 1974 (Ref. 4). The modifications affected the following parameters:

1. Load current
2. Mass flow rate
3. Channel area variation
4. Inlet stagnation pressure
5. The diagonalization angle
6. The active length of the channel
7. The normal and axial current density
8. The magnetic field strength B and distribution
9. The exit stagnation pressure

The details of these modifications are given in references 1 through 4.

Using the revised input data of Revision 5, it was clear from the preliminary computations that the exit conditions given by the designer could not be matched while retaining the subsonic flow conditions for which the channel was designed. Further study indicated that two main reasons contribute to the tendency towards supersonic behavior. The first reason is a small difference between the thermodynamic properties of the working fluid that are calculated by the STD codes and the values used by the designer. Table IV shows the difference in the value of the product of gas constant R by the ratio of specific heats γ . The second, and more important, reason is the difference between

the values of the transverse current density distribution J_y given by the designer and the values calculated by code MINIDIAGONAL- μ . Figure 18 shows the transverse current density J_y distribution for both cases. It shows that the average J_y computed by our codes is about 20% less than that of the designer. The lower value of the normal current density results in a weaker accelerating force on the gas. To counteract this effect the inlet velocity in our computation must be increased. This leads to supersonic flow conditions when the exit static pressure and Mach number are matched to the design values. Proceeding through the sonic point with code MINIDIAGONAL- μ leads to numerical problems at $M \approx 1.15$. The exact exit conditions of the designer could not be achieved with mid-channel Mach numbers less than this value. Fig. 19 (Computation STD5541) shows a typical supersonic operating condition with exit pressure and Mach number different than the designer's values. The difference between the values of the normal current density distributions used by the designer and that calculated from our codes is mainly due to the difference in values of the electrode voltage drops, as described in the previous section. Fig. 20 shows a comparison between the axial variation of the electrode voltage drop V_e calculated by our codes and those used by the designer, where the voltage drop is defined by $V_e = (U_{\text{CL}} B - J_y \text{CL} / \sigma_{\text{CL}})(D - \delta_a^* - \delta_c^*) - |V_F|$, where U_{CL} is the center-line velocity, σ_{CL} is the scalar conductivity, δ_a^* and δ_c^* are the anode and cathode displacement thicknesses and V_F is the Faraday voltage.

To demonstrate the cause-effect relation between the Mach number distribution and the variation of J_y , a computation was carried out with the channel in the Faraday connection with the designer's values of J_y specified as an input. Computation number STD5664 proved that the designer's exit conditions can be matched, and that the Mach number increases monotonically to one at the exit of the channel. Table V shows the inlet conditions and some of the results of run STD5664. A small difference between the inlet conditions in this calculation and the designer's values is attributed to the difference in the thermodynamic properties mentioned above.

After consultation with the designer (Re 5) it was agreed to increase the gas conductivity σ , the load current I_L , and the inlet gas pressure. Proceeding within these guidelines it was possible to

approach subsonic flow while maintaining the design exit conditions (Computation No. STD5705). Table VI shows the important parameters identifying this computation as well as some of the computed results.

The total power output is approximately 16 MW which is much larger than the 10.5 MW quoted by the designer. This is primarily because the conductivity of the gas has been raised from the designer's value of 7.3 mho/m at the entrance of the channel to 9.8 mho/m. The average value along the channel for the transverse current density J_y is 0.906 A/m^2 which is slightly below the designer's value of 0.92 A/m^2 . Figs. 21 through 25 show the axial variations of the centerline values of the Mach number, the gas pressure, the scalar conductivity, axial electric field, and the transverse current density.

Work is in progress to investigate other effects such as wall roughness, interelectrode shorting, effects of slag layers, and current-voltage characteristics by varying other parameters in a range around the conditions of run STD5705.

References

1. T. R. Brogan, Interim Loft Rev. 2.
2. T. R. Brogan, Interim Loft Rev. 4., October 18, 1974.
3. T. R. Brogan, Interim Loft Rev. 5., October 25, 1974.
4. T. R. Brogan, Telephone conversation, October 29, 1974.
5. T. R. Brogan, Telephone conversation, November 8, 1974.

TABLE IV

Comparison between the values used by STD
and the designer for the thermodynamic
quantity γR in the computation of operating conditions
for the U-25/MEPPSCO channel.

	<u>Inlet Conditions</u>	<u>Exit Conditions</u>
<u>Designer:</u>		
γR	359.06 m ² /K	356.0 m ² /K
Temp.	2787 K	2633 K
<u>STD:</u>		
γR	378.4 m ² /K	371.9 m ² /K
Temp.	2787 K	2651 K

TABLE V

Axial variation of performance parameter in computation No. STD5664
in the Faraday mode with the designer's values of the normal current density
for the MEPPSCO U-25 SOD Channel
Rough wall (R_{μ} -variable to match designer's c_f values,
code MINICOUPLD- μ), $\dot{m} = 50 \text{ Kg/s}$

X	U	TG	P	PLOC	PINT	MACH	SIGMA	BETA	JY	VF	VD	KLOC	KAV	PHI	HCON	HTOT	DDISC	DDISA	DELTA
0.00	851	2787	2.062	4.72	0.00	.85	8.54	.53	-.80	431	129	.45	.35	0	34.9	0.0	1.41	1.41	13.85
.20	862	2781	2.002	5.48	.27	.86	8.50	.60	-1.00	400	131	.38	.29	-121	32.7	.1	2.44	2.44	19.03
.40	873	2775	1.932	4.71	.52	.88	8.44	.62	-1.10	312	146	.33	.22	-281	27.3	.2	3.29	3.30	23.76
.60	879	2770	1.876	5.44	.79	.88	8.43	.63	-1.02	389	147	.38	.27	-443	26.5	.3	4.12	4.12	28.80
.80	882	2766	1.828	6.16	1.11	.89	8.40	.65	-.90	499	144	.45	.35	-594	27.8	.4	4.90	4.90	33.64
1.00	882	2763	1.790	6.13	1.46	.89	8.38	.66	-.87	521	154	.47	.36	-735	29.6	.5	5.74	5.74	37.71
1.20	887	2758	1.743	6.07	1.82	.89	8.34	.68	-.88	518	166	.47	.35	-880	30.7	.6	6.47	6.47	43.56
1.40	892	2753	1.696	6.00	2.18	.90	8.30	.70	-.88	516	180	.47	.35	-1031	31.5	.7	7.19	7.19	48.02
1.60	896	2749	1.651	5.92	2.54	.90	8.27	.71	-.89	513	193	.46	.34	-1187	31.9	.9	7.93	7.93	54.16
1.80	900	2744	1.604	5.85	2.91	.91	8.22	.73	-.89	512	207	.46	.33	-1350	32.2	1.0	8.64	8.64	57.42
2.00	905	2739	1.558	5.77	3.28	.91	8.19	.75	-.90	509	221	.46	.32	-1519	32.4	1.1	9.36	9.35	64.07
2.20	909	2734	1.513	5.71	3.66	.92	8.14	.77	-.90	509	234	.46	.32	-1693	32.4	1.2	10.08	10.08	69.78
2.40	913	2728	1.466	5.64	4.05	.92	8.12	.80	-.90	508	246	.46	.31	-1877	32.4	1.4	10.79	10.78	73.26
2.60	918	2723	1.419	5.60	4.44	.93	8.06	.82	-.91	509	260	.46	.30	-2067	32.4	1.5	11.51	11.50	77.99
2.80	922	2717	1.373	5.52	4.84	.94	8.04	.84	-.91	506	274	.46	.30	-2266	32.3	1.6	12.23	12.21	84.33
3.00	927	2712	1.327	5.46	5.25	.94	7.99	.87	-.92	505	287	.46	.29	-2473	32.1	1.8	12.95	12.93	90.96
3.20	931	2706	1.281	5.41	5.67	.95	7.95	.90	-.92	505	301	.45	.28	-2689	31.9	1.9	13.68	13.66	95.17
3.40	935	2700	1.234	5.36	6.09	.95	7.91	.93	-.93	506	315	.45	.28	-2915	31.7	2.0	14.43	14.41	98.82
3.60	940	2694	1.188	5.30	6.53	.96	7.87	.96	-.93	503	330	.45	.27	-3151	31.5	2.2	15.20	15.17	103.62
3.80	943	2688	1.143	5.23	6.98	.96	7.83	1.00	-.94	504	345	.45	.27	-3398	31.3	2.3	16.05	16.01	112.11
4.00	946	2682	1.098	5.18	7.44	.97	7.79	1.04	-.94	506	360	.45	.26	-3656	31.1	2.5	16.88	16.84	117.14
4.20	950	2675	1.053	5.14	7.91	.97	7.75	1.08	-.94	509	376	.45	.26	-3927	30.8	2.7	17.75	17.69	123.54
4.40	953	2668	1.008	5.11	8.40	.98	7.71	1.12	-.94	513	392	.45	.26	-4210	30.6	2.8	18.62	18.55	129.47
4.60	956	2662	.964	5.04	8.90	.98	7.67	1.17	-.95	512	407	.45	.25	-4507	30.3	3.0	19.58	19.50	134.42
4.80	958	2655	.920	4.99	9.42	.99	7.63	1.22	-.95	514	427	.45	.25	-4820	30.1	3.2	20.57	20.48	139.08
5.00	961	2647	.876	4.94	9.96	.99	7.60	1.27	-.95	516	445	.45	.24	-5149	29.8	3.3	21.63	21.52	145.48
5.20	961	2640	.833	4.90	10.52	.99	7.57	1.33	-.95	521	464	.46	.24	-5496	29.6	3.5	22.84	22.71	158.07
5.40	965	2632	.789	4.85	11.10	1.00	7.54	1.36	-.94	490	465	.45	.23	-5859	29.3	3.7	23.86	23.70	164.75
5.60	966	2626	.753	3.01	11.56	1.00	7.51	1.23	-.86	372	397	.40	.20	-6193	28.9	3.9	25.24	25.06	169.03

See Progress Report No. 32 (16 December 1973)
Appendix B, for a list of symbols

TABLE VI

Axial variation of performance parameter in computation
 No. STD5705 for Design Revision 5 of the MEPPSCO U-25 SOD Channel
 Rough wall (R_μ -variable to match designer's c_f values
 code MINIDIAGONAL- μ) $\dot{m} = 50$ Kg/s

X	U	TG	P	PIOC	PINT	MACH	SIGMA	BETA	JY	VF	VD	KLOC	KAV	PHI	HCON	HYOT	DDISC	DDISA	DELTA
0.00	834	2787	2.102	.46	0.00	.83	9.79	.51	-1.13	17	149	.14	.01	0	2.4	0.0	1.41	1.41	13.85
.20	857	2778	2.007	5.02	.16	.86	9.71	.59	-1.19	230	111	.25	.17	-50	14.9	.1	2.25	2.19	126.67
.40	866	2772	1.938	6.36	.46	.87	9.67	.61	-1.13	347	107	.33	.25	-143	20.8	.2	2.91	2.90	79.20
.60	868	2768	1.887	7.06	.83	.87	9.64	.63	-1.05	450	109	.40	.32	-254	24.8	.3	3.61	3.62	38.02
.80	871	2764	1.838	7.39	1.23	.88	9.60	.64	-.97	543	113	.47	.39	-378	28.0	.4	4.29	4.32	39.74
1.00	875	2759	1.790	7.37	1.64	.88	9.55	.66	-.95	564	126	.48	.40	-506	30.4	.6	4.99	5.02	43.23
1.20	883	2753	1.734	7.35	2.07	.89	9.48	.68	-.94	569	139	.49	.39	-638	32.1	.7	5.63	5.66	47.19
1.40	892	2747	1.679	7.33	2.51	.90	9.43	.70	-.94	574	152	.49	.38	-772	33.4	.8	6.27	6.30	49.93
1.60	901	2741	1.622	7.33	2.96	.91	9.34	.72	-.93	580	165	.49	.38	-910	34.3	1.0	6.89	6.92	55.70
1.80	910	2734	1.567	7.34	3.42	.92	9.27	.74	-.93	588	178	.49	.38	-1051	35.0	1.2	7.49	7.52	59.88
2.00	919	2727	1.511	7.36	3.89	.93	9.19	.77	-.92	596	190	.49	.37	-1197	35.6	1.3	8.08	8.11	62.88
2.20	928	2720	1.458	7.37	4.38	.94	9.12	.79	-.92	603	203	.49	.37	-1347	36.1	1.5	8.70	8.73	66.71
2.40	937	2713	1.403	7.39	4.88	.95	9.04	.82	-.91	612	216	.49	.36	-1501	36.5	1.6	9.29	9.32	71.24
2.60	947	2706	1.349	7.43	5.40	.96	8.96	.85	-.91	622	229	.49	.36	-1661	36.8	1.8	9.86	9.90	77.33
2.80	957	2698	1.295	7.47	5.93	.97	8.87	.88	-.90	631	241	.49	.36	-1826	37.1	2.0	10.38	10.42	81.52
3.00	966	2690	1.242	7.50	6.49	.99	8.78	.91	-.89	640	253	.49	.35	-1998	37.4	2.2	10.96	11.00	84.86
3.20	977	2682	1.188	7.55	7.07	1.00	8.68	.95	-.89	651	266	.49	.35	-2175	37.7	2.4	11.46	11.51	88.81
3.40	988	2673	1.135	7.59	7.67	1.01	8.58	.99	-.88	662	279	.49	.35	-2360	37.9	2.6	11.99	12.05	93.70
3.60	998	2665	1.083	7.64	8.29	1.03	8.48	1.03	-.87	672	293	.49	.34	-2552	38.1	2.8	12.52	12.59	97.42
3.80	1008	2656	1.033	7.66	8.94	1.04	8.38	1.08	-.86	681	307	.49	.34	-2752	38.4	3.0	13.10	13.18	104.43
4.00	1017	2647	.985	7.68	9.62	1.05	8.28	1.13	-.85	690	321	.49	.34	-2960	38.6	3.2	13.72	13.81	110.56
4.20	1024	2639	.940	7.67	10.32	1.06	8.18	1.18	-.84	697	336	.49	.33	-3177	38.8	3.5	14.44	14.54	115.09
4.40	1030	2630	.897	7.65	11.05	1.07	8.09	1.23	-.83	701	351	.49	.33	-3401	39.0	3.7	15.22	15.34	119.06
4.60	1031	2623	.860	7.56	11.81	1.07	8.02	1.27	-.81	700	367	.49	.32	-3634	39.2	4.0	16.27	16.40	123.02
4.80	1024	2618	.832	7.32	12.58	1.06	7.99	1.31	-.80	685	383	.48	.31	-3872	39.4	4.2	17.80	17.96	127.59
5.00	1013	2615	.809	7.11	13.37	1.05	7.99	1.35	-.79	671	402	.48	.30	-4114	39.6	4.5	19.68	19.86	134.58
5.20	995	2613	.792	7.11	14.16	1.03	8.01	1.37	-.80	676	423	.49	.30	-4360	39.7	4.8	22.09	22.24	142.41
5.40	981	2610	.772	5.93	14.95	1.02	8.03	1.36	-.75	549	416	.44	.25	-4603	39.8	5.0	24.60	24.83	165.80
5.60	960	2611	.762	3.65	15.57	1.00	8.05	1.20	-.67	282	350	.33	.15	-4792	39.7	5.2	27.61	27.89	253.31

See Progress Report No. 32 (16 December 1973)
 Appendix B, for a list of symbols

Fig.18. Comparison of the axial variation of the normal current density.

Fig. 19. Axial variation of centerline Mach number

Fig. 21. Axial variation of centerline Mach number

Fig. 22. Axial variation of centerline static pressure

Fig.. 23. Axial variation of centerline scalar conductivity

Fig. 24. Axial variation of axial electric field

Fig. 25. Axial variation of the normal component of current density

MEPPSCO U-25 SOD Channel, Revision 5

$$I_L = 3250A$$

Design values of loft, width, diagonalization,
skin friction.

Computation No. STD5702

(Rough wall - Code MINIDIAGONAL-μ)

45. Axial variation of the electrode voltage drop

$$V_{e,\epsilon} \equiv (E_{y\epsilon})(D - \delta_a^* - \delta_c^*) - |V_F|$$

 $V_e, E \times 10^{-2} (V)$

4

2

0

0

2

4

x (m)

6

A3-16

Fig. 40. Typical output current-voltage characteristics for the MEPPSCO U-25 Revision 5 design operating at 50 kg/s with inlet conductivity $\sigma \approx 9.8$ mho/m.

Fig. 1-3. The Output Characteristic of the MEPPSCO U-25 SOD Channel in the Diagonal Mode

Fig. 13. Diagonal generator notation and sign convention.

Fig. 14. Effect of electrode coating layer conductivity on overall electrical power output from a high-subsonic, diagonal generator design.

$M, J_y \text{ (A/cm}^2\text{)}$

Fig. 15. Effect of electrode coating on current density and Mach number distribution in a high-subsonic diagonal generator design.

CURRENT DISTRIBUTION

200 A/m contours

VOLTAGE DISTRIBUTION - 100 V contours

MEPPSCO U-25 SOD CHANNEL

DESIGN REVISION 5 - DIAGONAL CONNECTION

DESIGN VALUES of LOFT, WIDTH, DIAGONALIZATION
ANGLES, and SKIN FRICTION

$\dot{m}$ = 50.00 Kg/sec	I_L = 3250 A	U_{in} = 836 m/sec
p_{in} = 2.097 atm.	MW_e = 15.95 MW	T_{in} = 2887 K
p_e = 0.723 atm.	M_e = 1.04	δ_{in}^* = 1.41 mm

Code MINICOUPLD- μ Computation No. STD5702

APPENDIX 4

PROPOSED DEC PDP-11 REAL TIME COMPUTER
SUPPORT SYSTEM

APPENDIX 4

PROPOSED DEC PDP-11 REAL TIME COMPUTER SUPPORT SYSTEM

The following pages contain a price quotation for a PDP-11/40 base data logging and field computation system. This material was supplied by DEC (Digital Equipment Corporation.)

Although the system as listed is complete it is somewhat general and cannot be further specialized until our specific needs have been more clearly defined. In addition the system price as listed is based upon standard catalog prices and was not submitted as a bid, therefore the current price may be considered as an upper limit.

Two equipment substitutions (Items 10 and 11) will allow expansion of the stated system with 32 channel A/D capability to 256 channel A/D capability for the same total price, without any compromise in speed or versatility. Replacement of the TM-11 magnetic tape transport with a DEC tape unit will yield a savings of approximately 50% in the price of Item 11.

This savings applied to an outside vendor's 256 channel A/D converter will allow the stated system expansion at no additional cost.

digital

November 20, 1974

MEPPSCO

141 Pearl Street
Boston, MA 02110

Attn: Mr. Arthur Aframe

Dear Mr. Aframe,

I have included a quotation of a PDP-11/40 system as we discussed in our meeting of November 14, 1974. Please review the following as it pertains to the system.

Item 9 is only a basic unit cost. When the number of channels is determined, the price will rise accordingly. The cost will range above the \$13,000 mark if 224 channels or greater are required.

Support for this entire system is done from our Vienna, Austria office and can be contracted with the only variable being the service engineers' travel and living expenses.

I am looking forward to meeting with you here in Waltham so that we may demonstrate a similar system. After you have had an opportunity to review our quotation, please contact me so that we may further discuss your needs. Also, if further literature is required or if there are any questions, please feel free to contact me at any time.

Very truly yours,

Brian J. Reynolds
Sales Representative

enclosure

BJR/cos

A4-2

DIGITAL CORPORATION

PHONE: AC 617 897-5111 TWX: 710-347-0212 CABLE: DIGITAL MAYN. TELEX: 94-84-57

MAYNARD, MASSACHUSETTS 01754

DATE November 20, 1974
REFERENCE

NEAREST DIGITAL SALES OFFICE

TO MEPPSCO
141 Pearl Street
Boston, MA 02110
Attn: Mr. Arthur Aframe

Digital Equipment Corporation
235 Wyman Street
Waltham, MA 02154
Attn: Mr. Brian J. Reynolds

GENTLEMEN: THANK YOU FOR YOUR INQUIRY. WE ARE PLEASED TO QUOTE AS FOLLOWS

ITEM	QUANTITY	DESCRIPTION	UNIT PRICE	AMOUNT
1	1	PDP-11/40-BA - 11/40 central processor with 16K word core memory, ASR33 Teletype terminal and control (DL11-A), cabinet, and 4 training credits.	\$ 15,500	\$ 15,500
2	1	KT11-D - Memory management option. Permits access to 124K words of memory and provides protection and relocation. Includes KJ11-A.	2,480	2,480
3	1	MM11-U - 16K word expander core memory. Mounts in MF11-U. 980 nsec cycle time.	4,500	4,500
4	1	RK11-DE - 1.2 million word disk cartridge drive and control unit. Expandable to a total of 8 RK05 DECpack disk drives. 11 usec/word transfer rate, 70 msec average access time. Included cabinet has space for 3 additional RK05's.	11,000	11,000
5	1	RK05-AA - 1.2 million word moving head DECpack drive. 11 usec/word transfer rate, 70 msec average access time.	5,100	5,100
6	1	KW11-L Line Time Clock. Divides time into intervals of 16 2/3 msec (20 msec at 50 Hz line frequency). Mounts in a dedicated CPU slot.	300	300

TERMS: NET 30 DAYS, F.O.B. DIGITAL PLANT
FREIGHT CHARGES COLLECT
↓ DELIVERY SCHEDULE ↓

THIS QUOTATION SHALL REMAIN FIRM FOR 60 DAYS FROM THE DATE HEREOF, UNLESS MODIFIED IN WRITING BY DIGITAL EQUIPMENT CORPORATION PRIOR TO OUR ACCEPTANCE OF YOUR CONTRACT OFFER, AND IS SUBJECT TO CREDIT APPROVAL AND TO THE TERMS AND CONDITIONS HEREON AND ON THE REVERSE SIDE, EXCEPT THAT THE TERMS AND CONDITIONS UNDER WHICH DIGITAL SELLS COMPUTERS, COMPUTER OPTIONS AND EQUIPMENT OF THE DECsystem-10 COMPUTER SYSTEM ARE THE TERMS AND CONDITIONS ON THE FACE HEREOF AND IN THE STANDARD DECsystem-10 PURCHASE AGREEMENT IN EFFECT ON THE DATE HEREOF. ANY CONTRACT RESULTING FROM THE QUOTATION MUST BE SIGNED IN MAYNARD, MASSACHUSETTS BY A DULY AUTHORIZED REPRESENTATIVE OF DIGITAL EQUIPMENT CORPORATION.

DIGITAL EQUIPMENT CORPORATION

By *Brian J. Reynolds*
Brian J. Reynolds, Sales Representative

CUSTOMER

DIGITAL EQUIPMENT CORPORATION

MAYNARD, MASSACHUSETTS 01754

PHONE: AC 617 897-5111 TWX: 710-347-0212 - CABLE: DIGITAL MAYN. TELEX: 94-84-57

PLEASE REFER TO THIS QUOTATION NO. IN ALL CORRESPONDENCE AND ORDERS

DATE November 20, 1974

ITEM	QUANTITY	DESCRIPTION	UNIT PRICE	AMOUNT
7	1	BM873-YA - Restart/loader contains ROM with bootstrap program for paper tape, disks (RC, RF, RP), magnetic tape, DECTape, and cassette.	400	400
8	2	DR11-C - General Purpose Digital interface. Permits bidirectional 16-bit parallel transfers between the user's device and the UNIBUS. Includes all necessary interrupt, address, and control signals and all required cable connectors.	450	900
9	1	AR11 - Analog Real-Time Module. Including a 10-bit a/d converter, two 10-bit d/a converters, crystal controlled clock, scope control, 16-channel multiplexer, sample and hold circuit.	1,500	1,500
*10	1	AFC-11 - Master File A/D Converter	5,940	5,940
11	1	TM11-EA - 9-track magnetic tape transport and control unit. Expandable to a total of 8 TU10 transports. 45'in/sec, 800 bpi (industry compatible).	10,745	10,745
12	1	LA36 - DECwriter II	1,850	1,850
13	1	DL11-A - Current Loop (20mA) Serial Line Interface. 8-bit character size; 2 stop bits. (Specify speed.)	500	500
14	1	RSX11-M - FORTRAN IV	3,000	3,000
15	5	DD11-B - Peripheral Mounting Panel. Includes UNIBUS Connector Module M920. Accommodates up to 4 small peripheral controllers or 2 DF11's with DL11's and 2 small peripheral controllers.	250	2,500
* REFER TO ATTACHED ADDENDUM				
TOTAL ITEMS 1 THROUGH 15				\$ 63,715

CUSTOMER

DIGITAL EQUIPMENT CORPORATION

pdp11/40

Customer MEPPSCO

Date 11-20-74

DIGITAL Number _____

Serial Number _____

Configuration Worksheet

JANUARY 1974

Option No.	Mntg. Code	Bus Ld.	Option No.	Mntg. Code	Bus Ld.	Option No.	Mntg. Code	Bus Ld.
11/10-	PAN		H960-D	CAB	—	MR11-DB	2 SPC	2
11/40-B-A	CAB		H961-A	CAB	—	PC11	SPC+PAN	1
BA11-ES	PAN	—	KE11-E	(11/40)	—	PR11	SPC+PAN	1
BB11	SU	—	KE11-F	(11/40)	—	RC11-A	PAN	1
BM792-	SPC	1	KJ11-A	(11/40)	—	RF11-A	CAB	1
CD11-	SU+FS	1	KT11-D	(11/40)	—	RK05	PAN	—
CM11-	SPC+TT	1	KW11-L	(11/40)	1	RK11-D	SU+CAB	1
CR11-	SPC+TT	1	KW11-P	SPC	1	RP03	FS	—
DB11-A	SU	1+1	LA30-	FS	—	RP11-C	CAB+FS	1
DD11	SU (5)	—	LC11-A	SPC	1	RS11	PAN	—
DF11	DF	—	LP11-	SPC+FS	1	RS64	PAN	—
DH11	2 SU	2	LPS11-	SM PAN	2	TA11	SPC+PAN	1
DJ11	SU	1	LS11-	SPC+TT	1	TC11-G	CAB	1
DL11-A	SPC	1	LT33-	FS	—	TM11	CAB	1
DR11-B	SU	1	LT35-	FS	—	TU10	CAB	—
DR11-C	SPC	1	LV11-	SPC+FS	1	TU56	PAN	—
GT40	TT	1	ME11-L	SM PAN	1	VT05	TT	—
H720-	(BA11-ES)	—	MF11-U	2 SU	1	RM311-A	SPC	1
H960-CA	CAB	—	MM11-U	(MF11-U)	1	RR11	SPC	1

Mounting Codes

CAB —A cabinet is included.
 FS —Free standing unit.
 TT —Table-top unit.
 PAN —Panel mounted (10½")
 SM PAN—Small panel (5½")
 SU —System unit
 SPC —Small peripheral controller
 () —Option mounts in the same space as equipment within parentheses

Some options include 2 separate physical parts and are indicated by use of a plus (+) sign.

Standard Cabinets

digital

CABINETS					TERMINALS AND FREE-STANDING PERIPHERALS	
		TM11 TA10	RK11 RK45		LA36 (1)	AS233 (1)
					()	()
				CPU 11/40	()	()
					()	()

ENTER OPTION NUMBERS FOR PERIPHERALS IN APPLICABLE SPACES IN CABINETS & MOUNTING BOXES. INDICATE AMOUNT OF MEMORY AND CPU OPTIONS BY CIRCLING THE APPROPRIATE OPTION NUMBERS.

INDICATE QUANTITY WITHIN PARENTHESES (), WHEN MORE THAN 1.

MOUNTING BOXES		
EXTERNAL MOUNTING BOX	9	
	8	
	7	
	6	
	5	
	4	
	3	
	2	
	1	
	INTERNAL MOUNTING BOX	5
4		
3		
2		DR11-C D211-C A2-11 AM233-YA
1		RK11-D
		MM11-U (16K)
		MEMORY (16K)
		KE11-E KT11-D KE11-F KW11-F
		DL11-A
		11/40 CPU
INTERNAL MOUNTING BOX	3	
	2	
	1	MM11-L (8K) MEMORY (8K)
		11/10 CPU

INDICATE DD11'S WHERE REQUIRED

SHADING MEANS PREWIRED ASSEMBLY

11/40 CPU

11/10 CPU (10-1/2")