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Whole-Field Measurements in Gas-Phase Turbulent Flows

Paul E. Dimotakis and Dominique Fourguette

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The purpose of this experimental, nine-month effort was to investigate the scalar field in fully-developed, gas-phase, turbulent flows using planar index-of-refraction imaging at elevated pressure ($p \simeq 10\,\mathrm{atm}$). The motivation behind this work is to further our understanding of phenomena that rely on the behavior of scalar gradients, such as aero-optic effects, laser propagation through, and scattering by, gas-phase turbulent flows, as well as turbulent mixing and combustion. In this effort, we have used planar laser-Rayleigh scattering to image simultaneously the index-of-refraction field of a turbulent jet and the optical degradation of the planar laser probe beam caused by the turbulent flow-field. From these results, we have demonstrated that conducting these experiments at elevated pressure increases the index-of-refraction gradients and improves the signal-to-noise ratio over measurements conducted at atmospheric conditions. The optical degradation occurs in the jet-fluid region and manifests itself as a spatial amplitude modulation (streaks) in the laser sheet. This optical degradation illustrates the same loss of coherence undergone by laser beams and by coherent information when propagating through the turbulent atmosphere.

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Abstract

The purpose of this experimental, nine-month effort was to investigate the scalar field in fully-developed, gas-phase, turbulent flows, using planar index-of-refraction imaging at elevated pressures ($p \simeq 10\,\mathrm{atm}$).

The motivation behind this work is to further our understanding of phenomena that rely on the behavior of scalar gradients, such as aero-optic effects, laser propagation through, and scattering by, gas-phase turbulent flows, as well as turbulent mixing and combustion.

In this effort, we have used planar laser-Rayleigh scattering to image simultaneously the index-of-refraction field of a turbulent jet and the optical degradation of the planar laser probe beam caused by the turbulent flow-field. From these results, we have demonstrated that conducting these experiments at elevated pressure increases the index-of-refraction gradients and improves the signal-to-noise ratio over measurements conducted at atmospheric conditions. The optical degradation occurs in the jet-fluid region and manifests itself as a spatial amplitude modulation (streaks) in the laser sheet. This optical degradation illustrates the same loss of coherence undergone by laser beams and by coherent information when propagating through the turbulent atmosphere.

1. Introduction

When propagating through the atmosphere, laser beams are subject to several degradation mechanisms, such as blooming and self-focussing as well as refraction and loss of coherence caused by atmospheric turbulence. In the present work, we address the latter, namely the optical degradation caused by a non-uniform index-of-refraction medium.

The experiment reported here investigates the optical degradation mechanisms of a light sheet by a turbulent index-of-refraction field in a spatially- and time-resolved fashion using laser-Rayleigh scattering. Laser-Rayleigh scattering techniques have been instrumental in the recent past in our understanding of mixing and scalar-gradients in gas-phase turbulent flows (Dowling & Dimotakis 1990, Rosemann *et al.* 1992, Fourguette *et al.* 1993). In the experiments reported here, the instantaneous index-of-refraction distribution of a gas jet of ethylene (C_2H_4) into nitrogen (N_2) and the resulting optical degradation of the probe beam were measured using planar laser-Rayleigh light scattering. Preliminary results were presented at the 47$^{\text{th}}$ American Physical Society Meeting in Atlanta, GA (Fourguette *et al.* 1994). The experiment was carried out at elevated pressure not only to increase the index-of-refraction gradients but also to increase the signal-to-noise ratio of the light-scattering realizations. The enhanced index-of-refraction gradients increase the optical phase-turning angles (refraction angles) throughout the flow such as to clearly observe the focussing and defocussing effects of the turbulent flow on the laser-sheet. The optical distortions sustained by the laser sheet occur in the turbulent flow-field and are visible in the form of a spatial intensity modulation of the laser sheet (streaks). By using a laser sheet, as opposed to discrete laser beams (Wissler & Roshko 1992), it is possible to identify some of the flow structures responsible for the optical degradation and obtain two-dimensional information on the optical degradation.

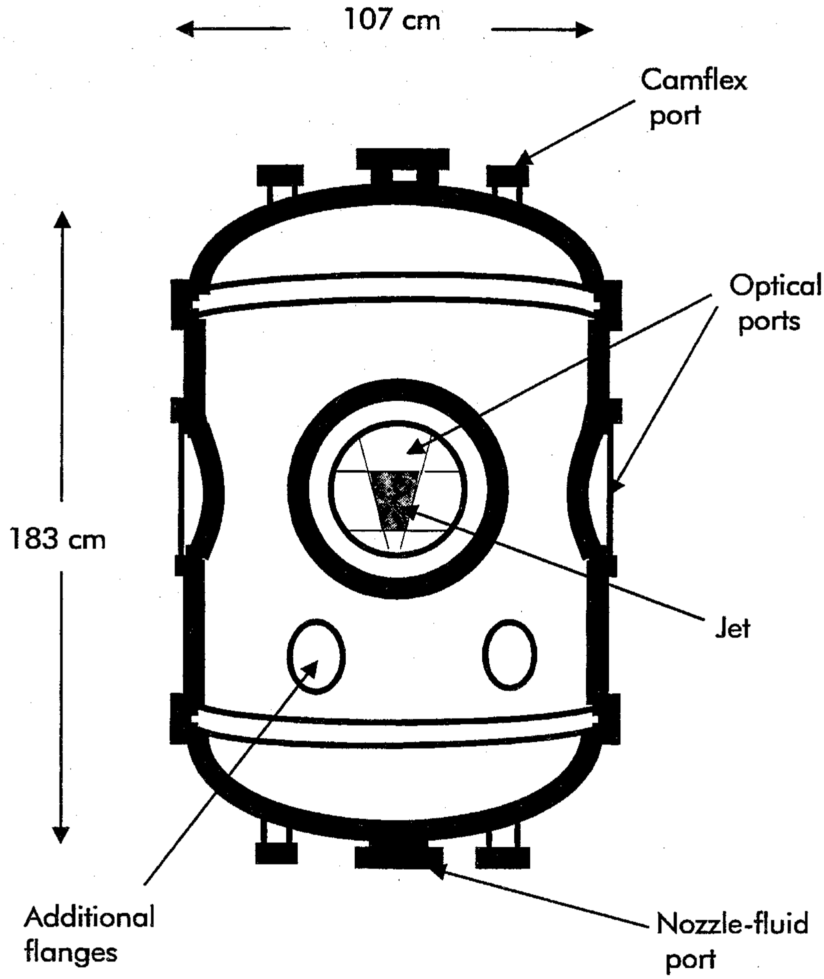

FIG. 1 Schematics of the HPCF

2. Experimental facility

The experiment was conducted in the High Pressure Combustion Facility (HPCF), depicted in Fig. 1.

This high-pressure reacting vessel (HPRV) was built under AFOSR and GRI (Gas Research Institute) joint sponsorship and has been used extensively for the study of chemically-reacting turbulent jets. A detailed description of the facility is given in Gilbrech (1991) and Gilbrech & Dimotakis (1992). A report detailing the design considerations (prepared by G. Mungal 1985, then Research Fellow in this group) is included in the Appendix of this report. This vessel is capable of handling pressures ranging from 0.1 to 15 atm. Its internal capacity is 1.43 m^3 with a diameter of 1.07 m. The HPRV is equipped with several flow management ports and 3 optical ports, consisting of pressure-sight, polished-glass windows, 5 cm thick and 25 cm in diameter. The jet-nozzle is 1 cm diameter and is directed upward inside the tank. A choked-flow delivery system ensures that the nozzle-fluid mass flux is independent of the ambient tank pressure.

The schematics of the optical diagnostics system is presented in Fig. 2.

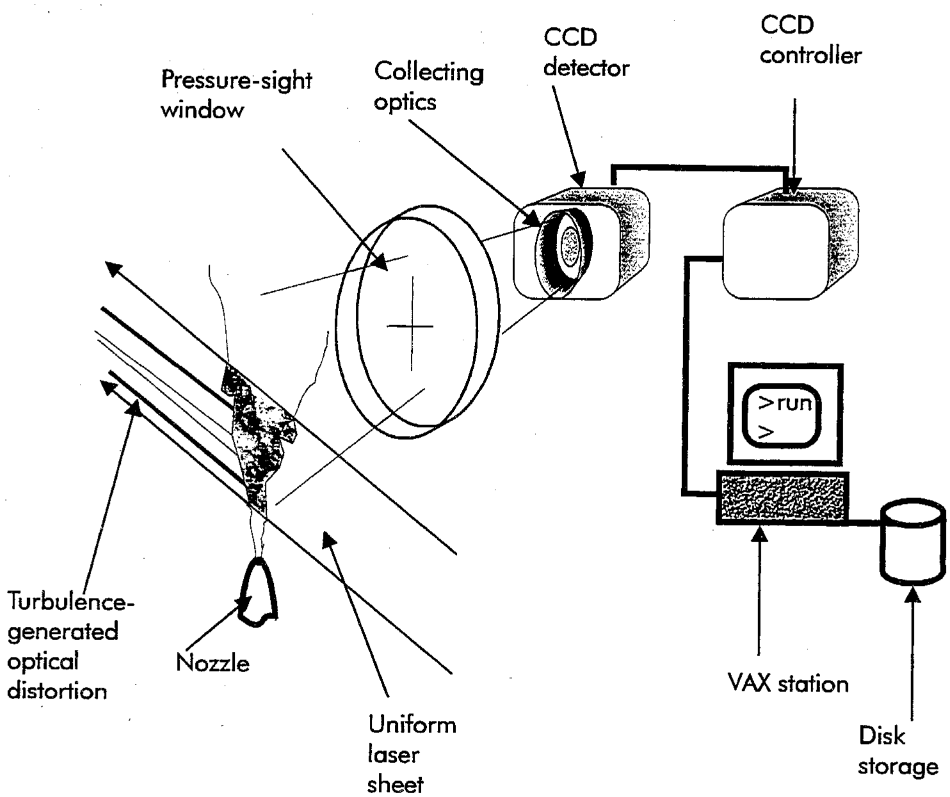

FIG. 2 Optical set-up

The beam of a green, frequency-doubled, Nd:YAG laser was shaped into a (planar) sheet, the sheet was passed through one of the optical ports, and intersected the jet-fluid along the nozzle-centerline. The laser sheet was subsequently trapped into a beam-dump mounted inside the vessel to minimize spurious beam-scattering. The Rayleigh-scattered light was collected at right angles outside the pressure vessel through a second optical port, and imaged with a camera lens (focal length = 85 mm and f# = 1.9) onto a liquid-nitrogen-cooled $1,024^2$ pixel CCD array. Each image was digitized and stored on a networked μVAX workstation.

3. Experimental technique

The index of refraction of a gas, $n \simeq 1$, depends on the pressure as

$$n = 1 + \beta \frac{p}{p_0} , \tag{1}$$

to a first approximation. In the above expression, p is the ambient pressure, p_0 is the reference pressure, and β depends on the species considered. Ethylene was chosen as the nozzle-fluid and nitrogen as the ambient fluid (Dowling & Dimotakis 1990). Ethylene and nitrogen represent an ideal gas-pair because the difference in their index-of-refraction guarantees significant index-of-refraction gradients while being density-matched (same molecular mass). Effects of buoyancy are thus obviated. For C_2H_4, $\beta = 0.721 \times 10^{-3}$, while for N_2, $\beta = 0.300 \times 10^{-3}$. From Eq. 1, it is clear that elevated pressure enhances index-of-refraction differences in a turbulent-mixing environment.

The index-of-refraction field was measured using planar laser-Rayleigh scattering. The Rayleigh-scattered intensity I_{sc} from a gas mixture is equal to

$$I_{sc} = I_0 \, N_s \left(\frac{\partial \sigma_{mix}}{\partial \Omega} \right) \Delta\Omega \, \eta_{opt} , \tag{2}$$

where I_0 is the intensity of the incident beam, N_s is the number of scatterers present in the probe volume, $\partial\sigma_{mix}/\partial\Omega$ is the Rayleigh cross-section of the illuminated gas mixture, $\Delta\Omega$ is the solid angle of the collecting optics, and η_{opt} is the collecting optics efficiency. At right angles, the differential Rayleigh-scattering cross-section of a gas, $\partial\sigma_{mix}/\partial\Omega$, depends on the wavelength of the incident light, λ, on the index of refraction of the gas, n, and on the number of scatterers, N_s, present in the illuminated volume, *i.e.*,

$$\frac{\partial \sigma}{\partial \Omega} = \frac{\pi^2}{\lambda^4} \left(\frac{n^2 - 1}{N_s} \right)^2 . \tag{3}$$

For gases, the ratio $(n^2 - 1)/N_s$ is independent of the density, to a first approximation, (*cf.* Born & Wolf 1993, p. 88), which makes the Rayleigh-scattering cross-section independent of the pressure.

The cross-section of a gas mixture is the sum of the mole-fraction-weighted cross-sections, *e.g.*,

$$\frac{\partial \sigma_{mix}}{\partial \Omega} = \sum_i X_i \frac{\partial \sigma_i}{\partial \Omega} \tag{4}$$

where X_i and $\partial\sigma_i/\partial\Omega$ are the mole fraction and scattering cross-section of the i^{th} species, respectively. In the case of a binary mixture, and when the relative cross-section of the two gases is known, the cross-section can be expressed as

$$\left(\frac{\partial\sigma}{\partial\Omega}\right)(\mathbf{x},t) = \frac{\partial\sigma_1}{\partial\Omega}X_1(\mathbf{x},t) + \frac{\partial\sigma_2}{\partial\Omega}\left[1 - X_1(\mathbf{x},t)\right] \tag{5a}$$

$$= \left[(\alpha-1)X_1(\mathbf{x},t)+1\right]\frac{\partial\sigma_2}{\partial\Omega}\ . \tag{5b}$$

where

$$\alpha \equiv \frac{\partial\sigma_1/\partial\Omega}{\partial\sigma_2/\partial\Omega}\ . \tag{6}$$

For the C_2H_4/N_2 gas-pair, $\alpha = 5.7$.

From Eq. 2, I_{sc} can be enhanced by increasing the number of scatterers in the probe volume, *i.e.*, the ambient pressure. The number of counts/pixel, N_{cts}, output by the CCD detector is directly proportional to the light scattered, I_{sc}, reaching each pixel, and, therefore, N_{cts} also depends on the pressure. The signal-to-noise ratio (SNR) of the measurements is proportional to

$$\mathrm{SNR} = \sqrt{\frac{N_{cts}}{N_{noise}^2 + N_{cts}}}\ , \tag{7}$$

where N_{noise}^2 represents the number of counts (squared) indentified with the camera noise.

In the photon-shot-noise-limited regime, *i.e.*when $N_{noise}^2 \ll N_{cts}$, the signal-to-noise ratio has the limiting behavior,

$$\mathrm{SNR} \propto \sqrt{N_{cts}} \Rightarrow \mathrm{SNR} \propto \sqrt{p}\ . \tag{8}$$

In summary, both the index-of-refraction gradients and the signal-to-noise ratio of the measurements are enhanced over that of measurements performed at atmospheric pressure.

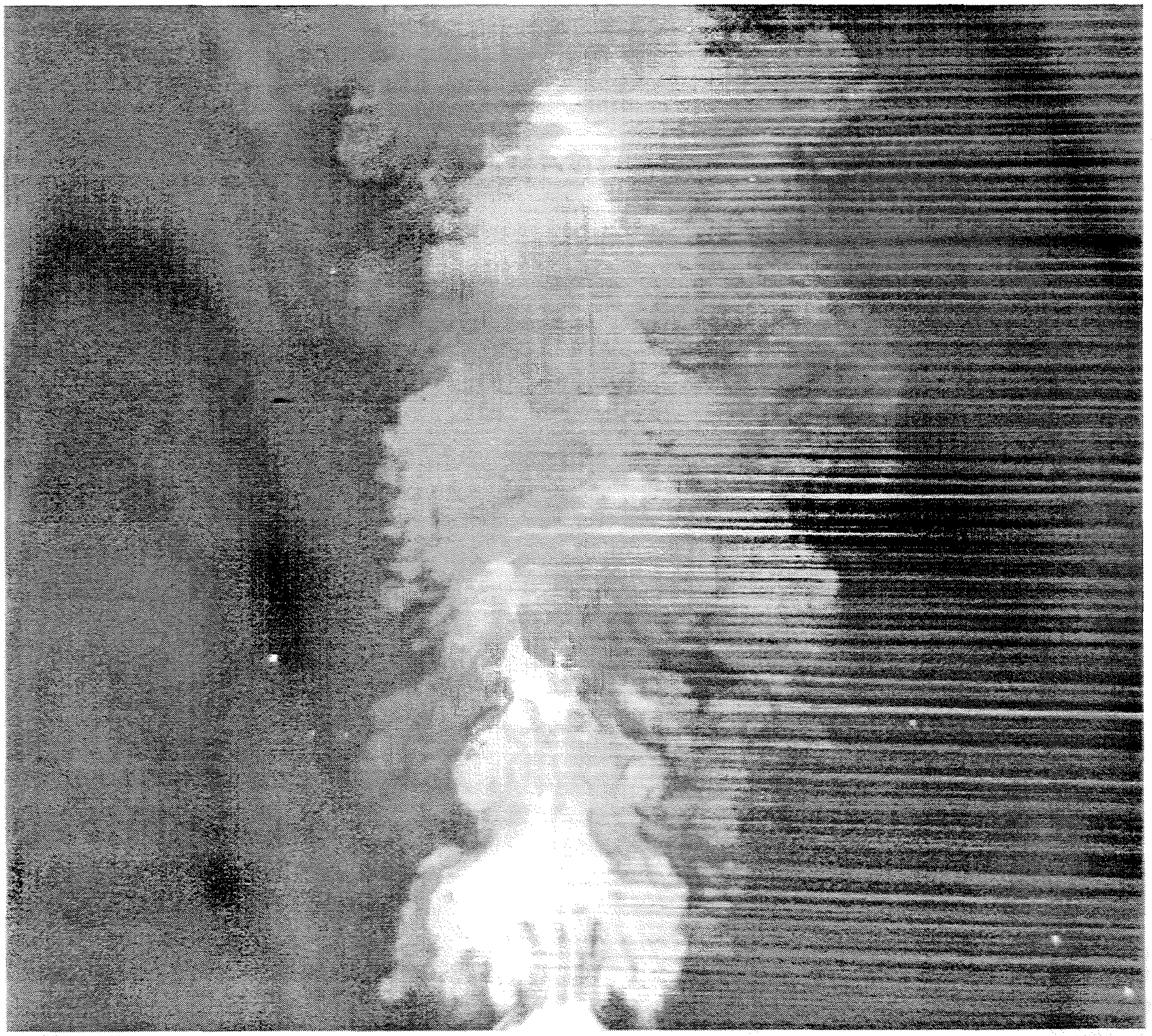

FIG. 3 Index-of-refraction field of a turbulent jet, $Re = 30,000$.

4. Results

Three individual realizations are presented in Figs. 3-5. For these experiments, the jet Reynolds number, based on the nozzle-exit parameters, was $Re = 3 \times 10^4$ to ensure fully-developed turbulent flow. The ambient pressure was 10 atm. Each pixel represents a volume of $140 \times 140 \times \ell\,\mu\mathrm{m}^3$, where ℓ is the laser sheet thickness, estimated to be $300\,\mu\mathrm{m}$. The imaged area begins at 3.3 nozzle-diameters

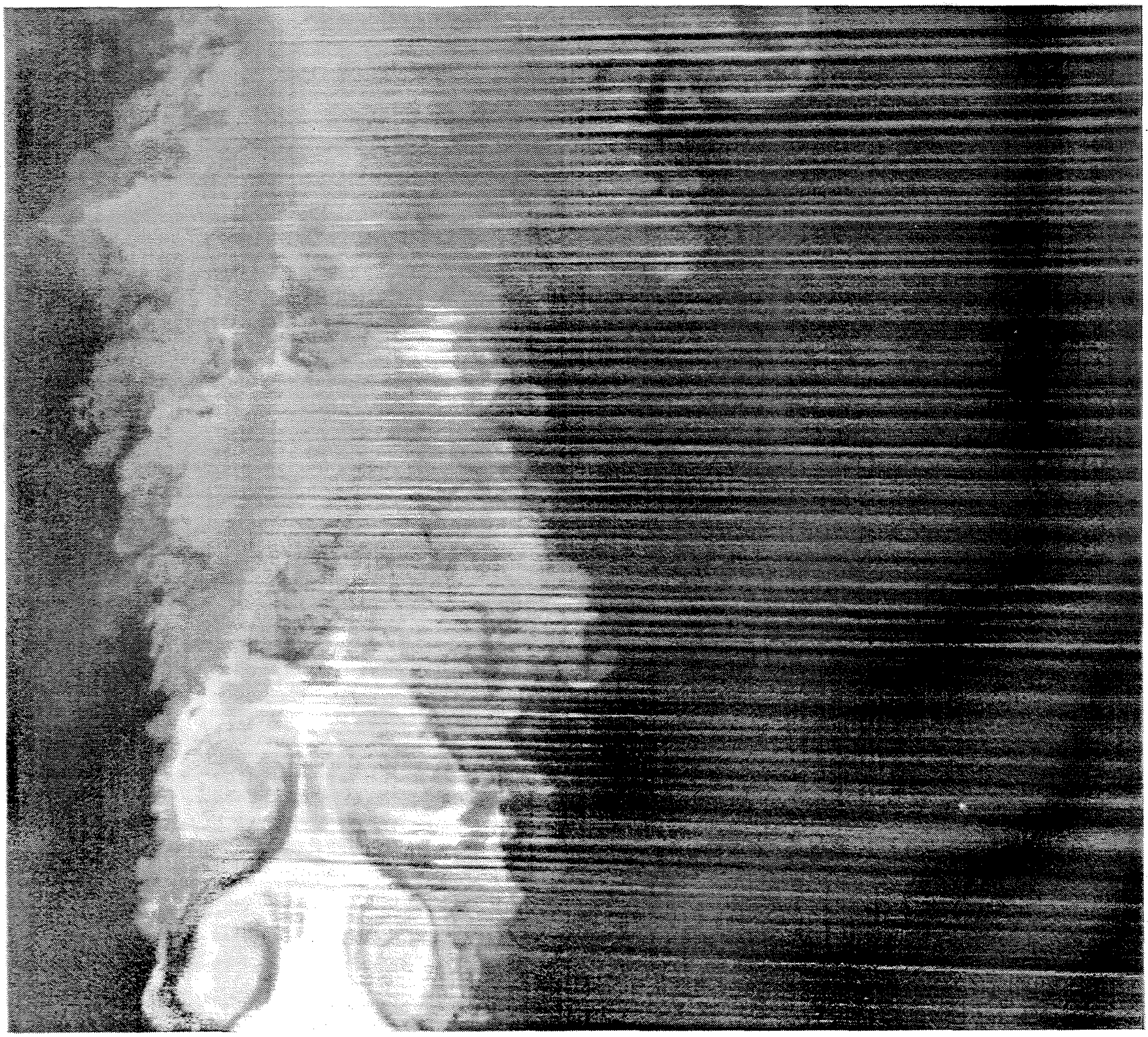

FIG. 4 Index-of-refraction field of a turbulent jet, $Re = 30,000$.

downstream of the jet-nozzle exit and extends an additional 6 nozzle-diameters downstream. Each realization is corrected for background illumination and then normalized for any non-uniformities in the laser sheet and the collecting optics.

The laser sheet propagates from left to right in all three images. The scattered light to the left of the jet flow-field can be seen to be uniform. The scalar scattering field there is solely composed of the unmixed reservoir species, N_2, *i.e.*, $X_1 = 0$

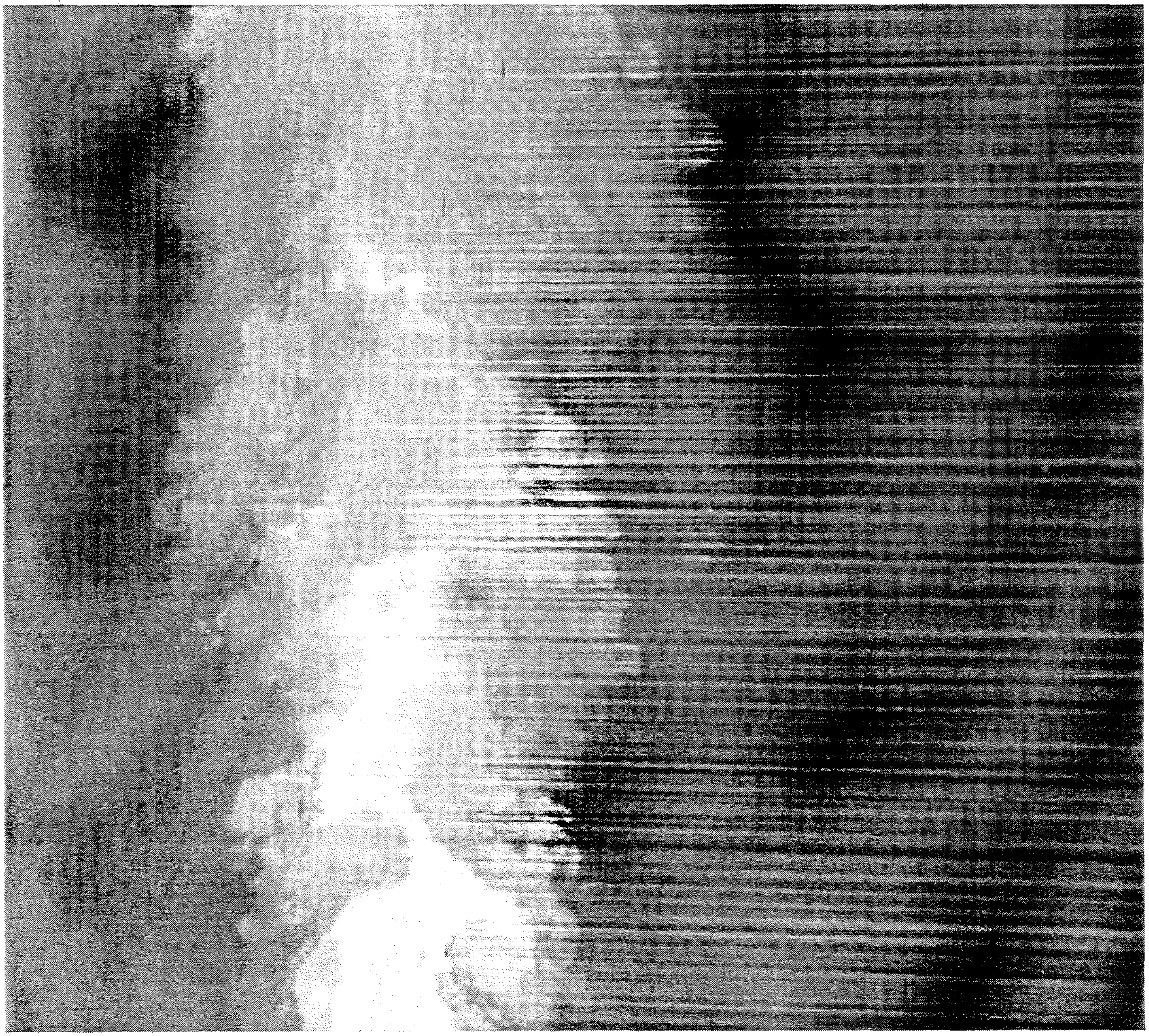

FIG. 5 Index-of-refraction field of a turbulent jet, $Re = 30,000$.

in Eq. 5b. This region of pure N_2 provides a reference to calculate the maximum measurement we can expect in the region of pure jet-fluid, *i.e.*, in the potential core where $X_1 = 1$.

High-intensity regions in the image indicate the presence of jet-fluid. Pure jet-fluid is found in the potential core close to the nozzle-exit. The grey regions in the image indicate that C_2H_4 has been stirred and mixed with the ambient gas,

N_2. Large-scale, mostly symmetrical, vortices resulting from the initial Kelvin-Helmholtz instability can be observed in Fig. 4. The jet can also display asymmetrical instabilities, as in Fig. 5.

Horizontal streaks can be seen to originate in the turbulent flow-field region and are clearly registered in the reservoir-fluid region to the right of the turbulent-flow region. These streaks are the result of optical aberrations caused by the index-of-refraction gradients associated with turbulent mixing. Individual wave-fronts forming the laser-sheet propagate through the flow-field and are refracted with a turning angle $\delta\theta$ proportional to the local transverse index-of-refraction gradient encountered along the path. We should note that the depth of field of the collecting optics is large enough to render the imaging insensitive to out-of-plane deflection of the probe beam (sheet). As a consequence, the data only register the in-plane distortions $\delta\theta$ for which we have recorded the complete index-of-refraction field, subject only to SNR limitations, *i.e.*,

$$\delta\theta = \int_0^L \frac{1}{n} \frac{\partial n}{\partial y} \, \mathrm{d}x \ , \tag{9}$$

where y denotes the direction locally transverse to the propagation of the laser sheet. The rays (normal to the wave-fronts) emerge from the turbulent-flow field with different refraction angles and propagate along a straight path through the ambient, uniform N_2 reservoir gas. Bright streaks are formed when several rays emerge from the turbulent flow with convergent turning angles, $\delta\theta$ and may form caustics within the image field-of-view. Dark streaks, between the brighter streaks, indicate areas of low ambient scattering intensity and are associated with locally divergent turning angles.

5. Conclusions

In the context of interest to the Air Force, these results illustrate the degradation mechanisms sustained by a laser beam when propagating through a turbulent region. The focussing (and defocussing) of the laser sheet indicate that turbulence-generated index-of-refraction gradients act as refractive lenses. Such index-of-refraction gradients, and the attendant aero-optics effects, can be enhanced by conducting such studies in an elevated-pressure environment. In the experiments reported here, the resulting refraction angles are sufficiently large to focus the rays emerging from the turbulent region within the planar-imaging detector's field of view. Consequently, the location where rays may form caustics can occur significantly closer to the turbulent-flow field and, in particualr, within the field of view of the CCD focal-plane array. This behavior could not have been obtained at lower (atmospheric) pressure, as the distance between the source of the optical distortion and the resulting caustics scales with the amplitude of the index-of-refraction gradient fluctuations (*cf.* Eq. 9).

6. Personnel

In addition to the Principal Investigator:

P.E. Dimotakis : Professor of Aeronautics & Applied Physics;

other personnel who have participated in the effort during the current reporting period are listed below:

W.K. Ching : Graduate Research Assistant;

E. Dahl : Member of the Technical Staff.

D.C. Fourguette : Senior Research Fellow, Aeronautics;

D.B. Lang : Member of the Technical Staff.

7. List of Publications

Fourguette, D.C, Dimotakis, P.E., and Ching, W.-K.,[1994] "Index-of-refraction imaging of turbulent jet flow obtained at high-pressure conditions," *Bull. Am. Phys. Soc.* **39**(9), 1936.

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Appendix

High Pressure Reactant Vessel

M. G. Mungal

1. Introduction

The High Pressure Reactant Vessel (HPRV) described below was designed as part of the 1984-86 GRI contract, in order to study the changes in flow dynamics as a reacting jet proceeds from a fully momentum driven to a fully buoyant regime. The facility will allow operation over a wide range of Reynolds number, Damkohler number and heat release rate. In addition, it should be possible in future to study reacting jets in crossflow, opposed flames or any other configuration which takes advantage of the wide pressure range of the facility.

2. Lab Expansion

The HF lab was expanded to accommodate the HPRV. Essentially the 19-foot roll-up door was moved south by 15 feet adding approximately 285 square feet of floor space to the already existing 600 square feet. Total cost was $32,500. This location permits the use of exotic chemicals as used in the current HF facility. Important features are: two entry/exit doors, reinforced concrete floor, two overhead whirlybirds for natural ventilation, overhead one-ton support rail with venting, 120/208V wiring, explosion proof ventilator and separate overhead lighting.

This expansion should provide the minimum required space to support the HPRV and related equipment. Please note that the building expansion plans are held at the CIT Physical Plant.

3. Operating Regime

3.1. Chemicals.

An important feature of the vessel is the ability to handle exotic chemicals. We investigated the choices of nitric oxide/ozone, silane/air and hydrogen/fluorine/nitric oxide. Difficulties with handling ozone (including difficulties in generation and spontaneous decomposition) eliminate the first choice in a similar manner as it did for the reacting shear layer. Silane produces particles which seemed unattractive for cold-wire thermometry and some aspects of laser diagnostics. Our considerable experience with hydrogen/fluorine/nitric oxide at low and high heat over a wide Damkohler number range make them the obvious choice for use in the facility.

3.2. Sizing.

The vessel was sized to be 3 1/2' diameter by 6' high. The diameter was determined by the requirement of low recirculating velocity of a confined jet (see Appendix 1) while the height was set to be one half of the available floor to ceiling height. This compromise allows reasonable access to the vessel within the confines of the lab. We have used a nominal design consisting of u_o = 60 m/s, d_o = 1/2 cm, ϕ = 20 (L/d_o = 200). This yields Re = 20,000 at 1 atm and Re =

200,000 at 10 atm. The choice of $\phi = 20$ is preserved in order to allow comfortable burning of most hydrocarbons at low/moderate/high pressure. Appendix 1 shows that under these conditions the recirculating velocity will be 5.5% of the centerline velocity at the flame tip when operating without coflow, while Appendix 2 shows that the jet will be momentum driven from burner lip to flame tip.

3.3. Flow Regimes.

The important numbers for this study are

$$Re = \frac{u_o d_o}{\nu} \quad \text{(Reynolds No.)}$$

$$Fr = \frac{u_o^2}{g d_o} \quad \text{(Froude No.)}$$

$$Da = \frac{\tau_m}{\tau_c} \quad \text{(Damkohler No.)}$$

Typical case:

$u_o = 6000$ cm/s $\quad d_o = 1/2$ cm $\quad Re = 20{,}000$ @ 1 atm. At $x/d_o = 200$, $u_c = 186$ cm/s, $\delta = 0.44\ x = 44$ cm $\tau_m = \delta/u_c =$ .24 sec. Start up time to travel from $x = 0$ to $x = L$ is given by

$$T = \frac{1}{2(.44)} \frac{\delta}{u_c} = 1.14\ \tau_m \simeq \tau_m$$

$$\dot{m}_o = \rho_o\ u_o\ A_o = 1.4 \times 10^{-3}\ \text{kg/sec}$$

$$M = \text{mass in tank} \simeq 2.0\ \text{kg}$$

$\therefore \; M/\dot{m}_o = 1400$ secs.

The more meaningful quantity is $M/\phi\dot{m}_o = 70$ secs for $\phi = 20$ (the tank volume will have approached stoichiometric proportions). We would like the run to be complete in about 1/10 of this time. A typical run would consist of starting time ($2\tau_m$) plus 30 local structure passage times which is approximately 7.7 secs. Thus the combination of $M, \dot{m}_o, \phi$ and run time appears reasonable. All of the above assumes no co-flow. However, if we include the co-flow

$$\frac{\dot{m}_j}{\dot{m}_o} = 0.32 \left(\frac{\rho_\infty}{\rho_o}\right)^{1/2} \left(\frac{x}{d_o}\right)$$

(from Ricou & Spalding) or

$$\dot{m}_j \sim 1/3 \left(\frac{x}{d_o}\right) \dot{m}_o = 66 \; \dot{m}_o.$$

at the flame tip. Hence the co-flow requirement is $\dot{m}_T = 66 \; \dot{m}_o = 9.4 \times 10^{-2}$ kg/sec at 1 atm. At 200 psig this becomes 1.3 kg/sec which is approximately the flow rate of one side of the HF shear layer (note: 1.25 kg/sec ~ 1800 scfm). These rates dictate an exhaust valve C_v of approximately 20. Based on the above flow rates it is assumed that no co-flow is used for exotic gases and co-flow (air) may be used for hydrocarbon fuels.

Possible Run Conditions:

$P = 1$ atm, $u_o = 6000$ cm/sec, $d_o = 1/2$ cm, $Re = 20{,}000$, $Fr = 7.3 \times 10^4$, $\dot{m}_o = 1.4 \times 10^{-3}$ kg/sec. If we keep $\dot{m}_o$ same, P same, d_o variable, then $u_o = 60$ cm/sec, $d_o = 5$ cm, $Re = 2000$, $Fr = .73$. This represents a change of 10^5 in Fr as we proceed from the far-field to the near-field of the jet. This type of experiment, to achieve a significant Froude No. change, was suggested by E. E. Zukoski.

Similarly at P = 10 atm, u_o = 6000 cm/sec, d_o = 1/2 cm, Re = 200,000, Fr = 7.3×10^4, $\dot{m}_o = 1.4 \times 10^{-2}$ kg/sec and at P = 0.1 atm, u_o = 6000 cm/sec, d_o = 1/2 cm, Re = 2,000, Fr = 7.3×10^4, $\dot{m}_o = 1.4 \times 10^{-4}$ kg/sec. These examples represent changes in Reynolds No. (via changes in pressure) at fixed Froude No. At both P = 10 and 0.1 atm, one can also consider the possibility of changing d_o while keeping $\dot{m}_o$ fixed to produce significant changes in Froude No.

Disguised in these examples (by changing P) is the fact that the chemical time changes with absolute pressure (for fixed concentrations of reactants). If we take

$$\tau_m = \delta/u_c = 0.44x/u_c = \frac{.071}{(\rho_o/\rho_\infty)^{1/2}} \left(\frac{x}{d_o}\right)^2 \frac{d_o}{u_o}.$$

Then for Da = τ_m/τ_c = 10 (fast chemistry) we would require

$$Da = .071 \left(\frac{x}{d_o}\right)^2 \frac{d_o}{u_o} \cdot \frac{1}{\tau_c} = 10.$$

Suppose past $\frac{x}{d_o}$ = 25 (far-field begins) we require Da = 10, then this requires τ_c = .37 msec. This appears reasonable in the context of what has been achieved in the HF shear layer experiments.

Since we assume ϕ = 20 we anticipate a typical low-heat run as 5% F_2/N_2 jet fluid discharging into 1/4% H_2/N_2 (with some NO) with T_{flm} ~ 44° K. Moderate heat might consist of 20% F_2/N_2 as the jet fluid with 1% H_2/N_2 (plus NO) with T_{flm} ~

186° K. The assumption here is that F_2 is the jet fluid, with H_2 in the reservoir in order to minimize the "smell" and cleanliness problems in the tank. It is clear that F_2 as the (low-concentration) reservoir and H_2 as the (high-concentration) jet would allow higher heat to be achieved, but such a decision is best deferred at this time until some run experience is obtained. High heat is, of course, obtainable with hydrocarbons. For the choice of chemicals quoted here it should be possible to use CHEMKIN to make a good estimate of the chemical time, thus ensuring high Damkohler numbers.

In summary then, the design allows an axial distance of 100 cm in which to study the development of either the near-field or far-field of either a momentum driven or buoyant reacting jet. Pressure, while it provides a significant Reynolds No. range capability, also changes the Damkohler number for fixed reactant concentrations so that some caution is required to unscramble Reynolds No. effects from Damkohler No. effects. The same, of course, is also true for interpretation of Froude No. effects.

4. Reactant Vessel

The vessel is being fabricated by California Tank & Mfg. Corp. (see Appendix 3). It is essentially 42" diameter, 72" high with 3/8" head and shell (see Fig. 1). The vessel is designed to ASME code, is stamped and National Board Registered. Working pressure is 0 to 200 psig at 300 °F. Relevant numbers are:

1. Tensile strength of steel 70,000 psi

2. Yield (typ) 38,000 psi

3. Factor of 4 safety 17,500 psi

4. 70% for welds (no X-ray) 12,250 psi

5. $\sigma = \frac{pr}{t} = \frac{200.21}{3/8} = 11,200$ psi

The heads of the vessel are removeable (for full access and lining capability at high heat) and each contains four 3" flanges (for coflow) and one 6" flange for jet nozzles or exhaust / optical access. The shell contains six 3" flanges, four 1-1/2" flanges and a single 16" manhole for access. The 3" flanges are diametrically opposed in order to allow for possible line of sight absorption or ignition capabilities. Optical access is provided by three 10" windows designed to sit on 12" studding flanges. The windows are positioned 4" above the vessel centerline to maximize the jet axial station that can be viewed. In addition, there are 44 internal tabs for use in supporting internal hardware. We have requested that all open seams be welded, ground smooth, free of pin holes with no severe weld undercutting and all sharp corners be rounded to 1/16" (min) radius. The vessel will be stress relieved by the manufacturer before the studding flanges are faced off for the O-ring seals. Caltech will witness the vessel hydrotest at 300 psig for 30 minutes. Please note that the original plans for the vessel are held by G. Yamamoto of CES.

The following sections will describe some of the features of the vessel that are important for this work.

4.1. Optical Windows.

The windows are 2-1/2" thick, 10" diameter pyrex windows, together with window mounts supplied by Pressure Products Co. The design uses a studding flange to allow the window to be as close as possible to the tank wall. The window holder is teflon (PFA) coated for compatibility with our chemicals (see Appendix 4). Schieren tests were performed on the three possible choices of glass: 1) soda lime, 2) tempered pyrex, 3) polished tempered pyrex. We have chosen the third option because the soda lime contained numerous bubbles and the polished pyrex contained less scratches than the tempered (unpolished) pyrex. The glass is by no means optical quality, but is designed for 1500 psi (i.e. safety factor of 7.5)

4.2. Relief Valves.

The relief valve is a 1 1/2", 316 s.s. Masoneilan Camflex valve with Taylor 440R controller (see Appendix 5). This allows one to establish a relief setting of 0 to 250 psig with suitable span adjustment. This system will respond (in about 1 second) to overpressure and restore the vessel to its preset pressure. The Camflex C_v is 30 which should easily meet the requirements of coflow at 200 psi should it be desired.

Additional relief is provided by a 3" inconel FIKE burst diaphragm. This system is set to burst at 275 psig (at 300°F) to prevent against accidental overpressure. It is important to note that neither of these systems can protect against overpressure due to sudden ignition of a combustible mixture within the vessel. In this case the design of the flow system must guarantee that ignition always occurs or that a stoichiometric unburned mixture must not exist in the vessel at any time.

4.3. Teflon Coating.

The vessel will be coated with .005" pinhole free Black FEP teflon (see Appendix 6). The coating is actually clear FEP on a black base but it is believed that this provides optical (stray light absorption) advantages over the much more common green FEP. The coating covers all wetted areas of the inside of the tank, including the flange faces and O-ring grooves. The coating will be done by Thermech Engineering Corp. Caltech will witness the test for a pinhole free coating.

4.4. Tank Mounting.

A mounting arrangement for the tank has been chosen so that the base of the tank is 4' from the floor while the top is 2' from the ceiling. This allows the lower lid to be dropped down and the head to be lifted free of the shell. In addition it moves the 10" windows to be 7' above the floor which we consider a desirable feature from the point of view of window blowout and laser beam access. It should be noted that this arrangement assumes that the jet will be introduced from below so that the window offset has been made with this in mind. An additional important feature is that it is possible to rotate the head by 45 degrees with respect to the shell thus allowing the 3" ports to clear the overhead rail. The mounting arangement has been approved by C. D. Babcock, and will be built by CES.

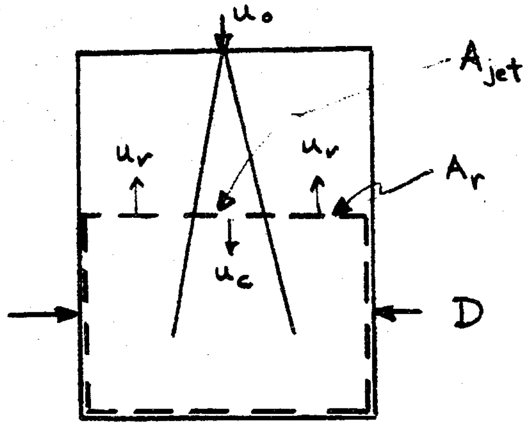
4.5. Control Panel / Gas Handling.

The control panel is not yet designed. It is clear that eliminating the coflow for exotic chemicals simplifies the design considerably since one does not have to provide the plumbing and mixing vessels to supply the coflow of exotics, nor does one have to process a large amount of toxins during the run before discharging to atmosphere. A mixing vessel technique will be used for the reservoir gas but either a mix-on-the-fly technique or a mixing vessel technique will be used for the jet fluid. Once again there is a considerable savings if F_2 were used as the reservior fluid with H_2 as the jet fluid, but it is believed that at this point, the design should be made assuming that F_2 is the jet fluid with the possibilities of interchange later on. These aspects have been discussed in detail with R. Gilbrech, with the final design to be made at a later date.

4.6. Downstream Exhaust.

The exhaust from the vessel will be treated by bubbling through NaOH solution as is done in the current HF shear layer work. When using exotic chemicals without coflow the exhaust flow rates are quite manageable. With coflow, the assumption is that a hydrocarbon fuel will be used in which case the exhaust will be vented directly to atmosphere. The possibility of tieing the exhaust line into the HF downstream bags remains an option at this time. For sub-atmospheric work it is assumed that the relief valve will remain closed and the tank pressure will rise during a run (this prevents the NaOH being sucked back into the tank). The system can then be flushed under positive pressure after such a run.

Appendix 1: Recirculating Flow



Consv. of mass: $\dot{m}_j = \rho_\infty u_r A_r$ or

$$0.32 \left(\frac{\rho_\infty}{\rho_o}\right)^{1/2} \left(\frac{x}{d_o}\right) \dot{m}_o = \rho_\infty u_r A_r \qquad \text{(Ricou \& Spalding)}$$

or

$$\frac{u_r}{u_o} = 0.32 \left(\frac{x}{d_o}\right) \frac{A_o}{A_r} \left(\frac{\rho_o}{\rho_\infty}\right)^{1/2}$$

and

$$\frac{u_c}{u_o} = 6.2 \left(\frac{\rho_o}{\rho_\infty}\right)^{1/2} \left(\frac{d_o}{x}\right) \qquad \text{(Chen \& Rodi)}$$

$$\therefore \frac{u_r}{u_c} = 0.052 \left(\frac{A_o}{A_r}\right) \left(\frac{x}{d_o}\right)^2$$

$$A_r = \frac{\pi}{4} D^2 - A_{jet} = \frac{\pi}{4} (D^2 - (.44x)^2)$$

$$\therefore \frac{u_r}{u_c} = \frac{0.052\left(\frac{x}{d_o}\right)^2}{\left(\frac{D}{d_o}\right)^2 - \left(.44\frac{x}{d_o}\right)^2}$$

For

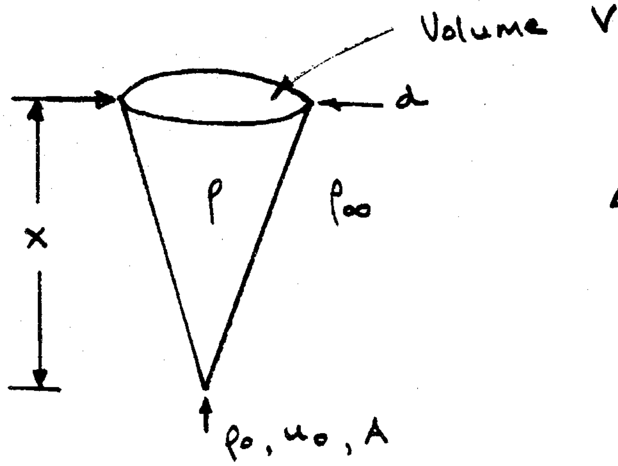
D = 42 inch = 107 cm

d_o = 1/2 cm

x/d_o = 200

$\frac{u_r}{u_c}$ = .055 = 5.5%

Appendix 2: Buoyancy



$\Delta\rho = \rho_\infty - \rho$
$d = 0.44x$

Require

$$\frac{\Delta\rho \; V \; g}{\rho_o \; u_o^2 \; A} < \text{const}$$

or

$$\frac{1}{3}(.44)^2 \; \frac{\Delta\rho \; g \; d_o}{\rho_o \; u_o^2} \left(\frac{x}{d_o}\right)^3 < c$$

Comparing with Becker & Yamazaki

$$\left[g\left(\frac{\rho_o}{\rho_\infty}\right)^{1/2} \frac{d_o}{u_o^2}\right]^{1/3} \left(\frac{x}{d_o}\right) \left(\frac{\rho_\infty}{\rho_o}\right)^{1/2} < 5$$

or

$$\left(\frac{\rho_\infty}{\rho_o}\right) \frac{g d_o}{u_o^2} \left(\frac{x}{d_o}\right)^3 < 125$$

implies $c = 8$ if $\Delta\rho = \rho_\infty$ (a worst case).

Hence at $u_o = 60$ m/s, $d_o = 1/2$ cm, $\frac{x}{d_o} < 209$ for momentum driven regime.

CALIFORNIA *Tank* & MFG. CORP.

P. O. BOX 5100 · 5674 CHERRY AVE. · LONG BEACH, CALIF. 90805
PHONE (213) 774-7370 · (213) 423-0927

January 3, 1985

California Institute of Technology
Graduate Aeronautical Laboratories 301-46
Pasadena, California 91125

Attention: Dr. M. Godfrey Mungal

Reference: Your letter of December 21, 1984
CTMC Estimate #4192 Revised

Gentlemen:

Per your invitation, we are pleased to re-quote on the following:

1 Pressure Vessel for gas service, 42" diameter x 6'0" O.H. 200# W.P. @ 300°F and full vacuum, ASME Code, with flanged heads, fabricated from 3/8" material thru out, with additional nozzles, stress relieving and machining as revised from previous quote. "O" ring supplied with unit will be neoprene test gaskets only. Bolts will be supplied for 42" flange and ~~14"~~ manhole only. 16"
Painting and coating to be done by "others".
4910# Estimated Weight Price Each ~~$15,[illegible].00~~ 15,950.00

Telephone
10-Apr-8

The above is quoted per your sketches of December 12, 1984 and (5) pages of notes.

The above vessel is quoted f.o.b. trucks our shop, Long Beach, California, and any applicable taxes are extra. Terms 1% 10 days, net 30 days.

Thank you for the opportunity of quoting on your needs, and we hope to be favored with your valued order.

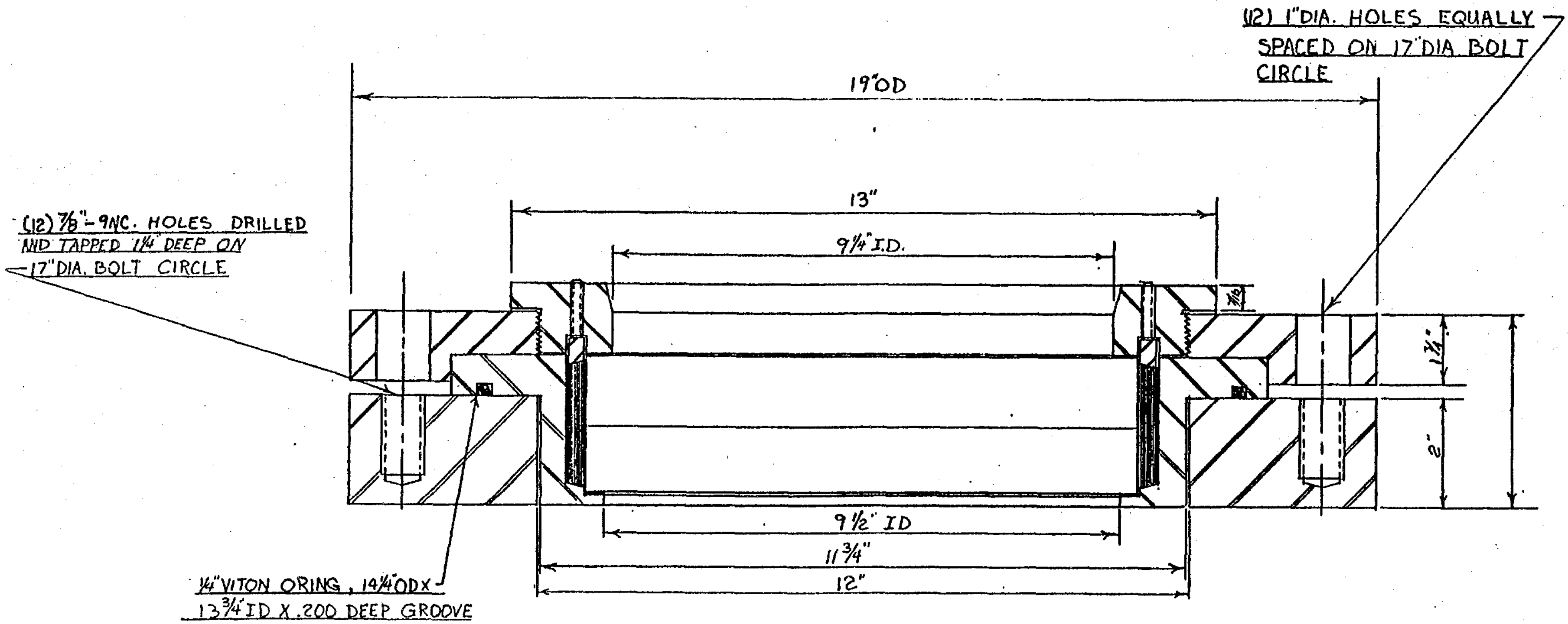
Sincerely yours,

CALIFORNIA TANK & MFG. CORP.

G. Dennis Hume
General Manager

GDH lh

Appendix 4



REVISIONS		
DATE	NO.	TITLE

SPECIAL 10"-150PSI MODEL "I" W/ 12"-150PSI DRILLING

PresSure Products Co.

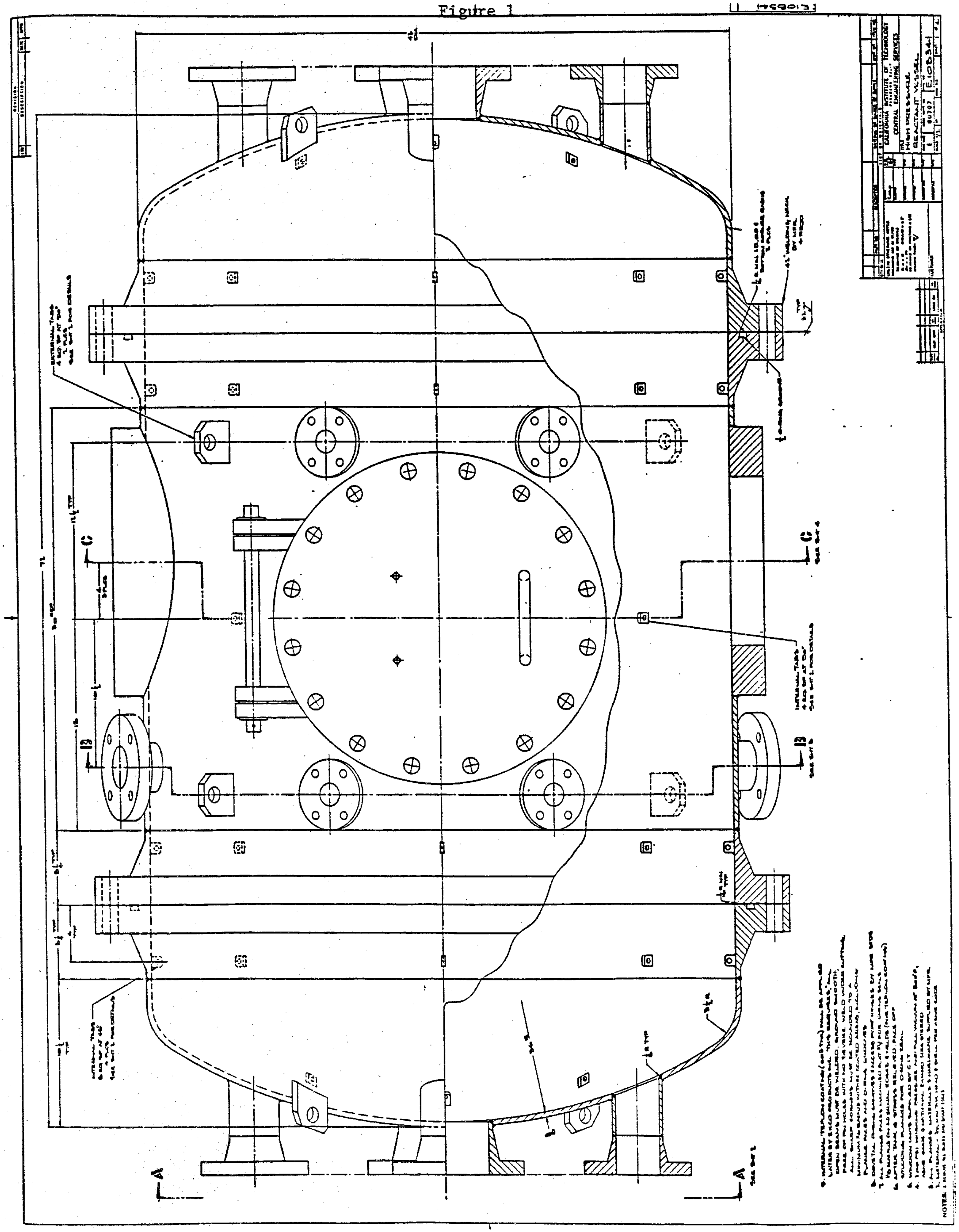
HI PRESSURE HI TEMPERATURE SIGHT GLASSES

PHONE 344-3511

P. O. BOX 6656
CHARLESTON, W. VA.

SCALE	DRAWN	CHECKED	APPROVED	ORIG. ISSUE	
NONE	CRF			12/20/81	12231-11259

Figure 1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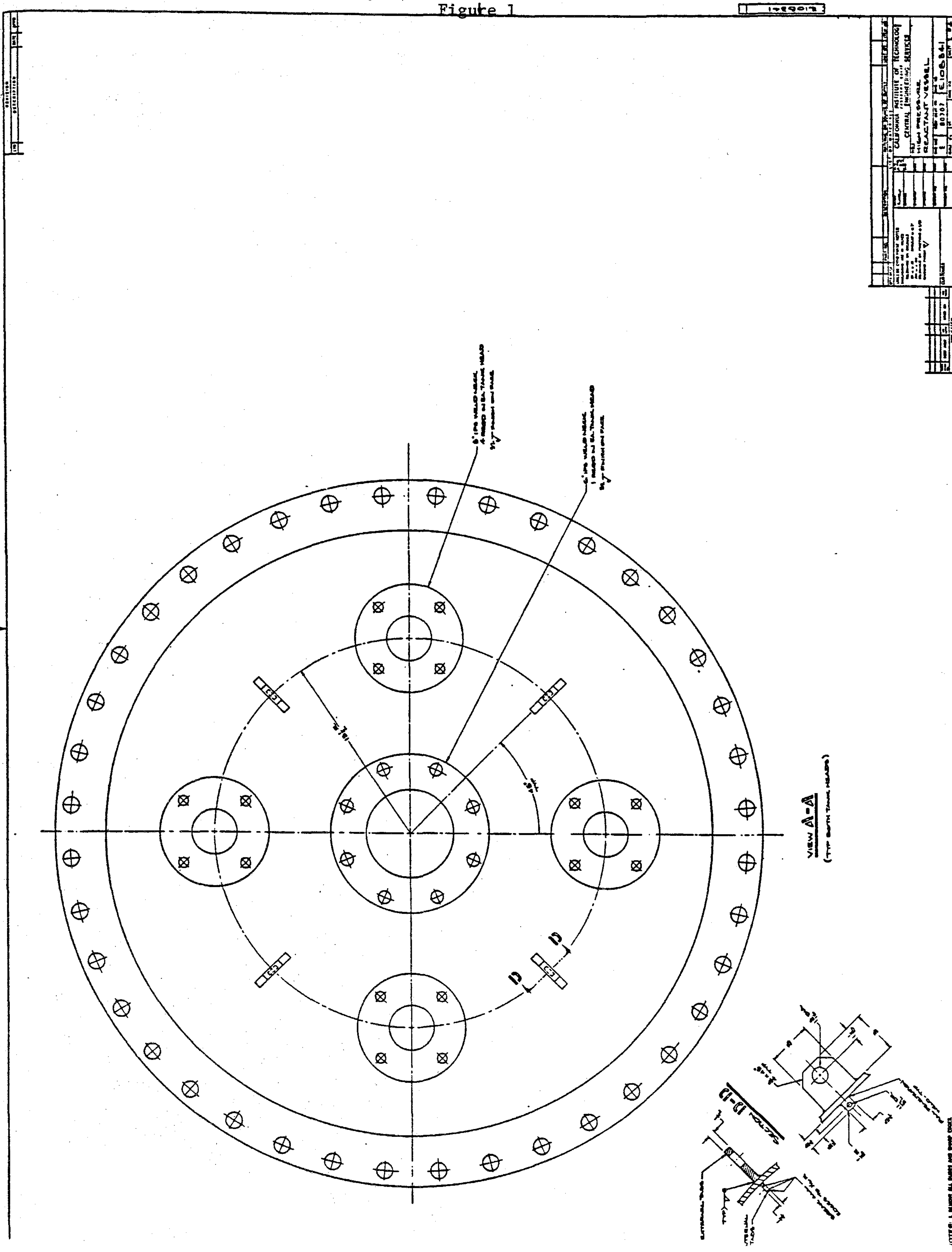
HIGH PRESSURE
REACTANT VESSEL
E10634-1
A
B
C

Figure 1


VIEW A-A
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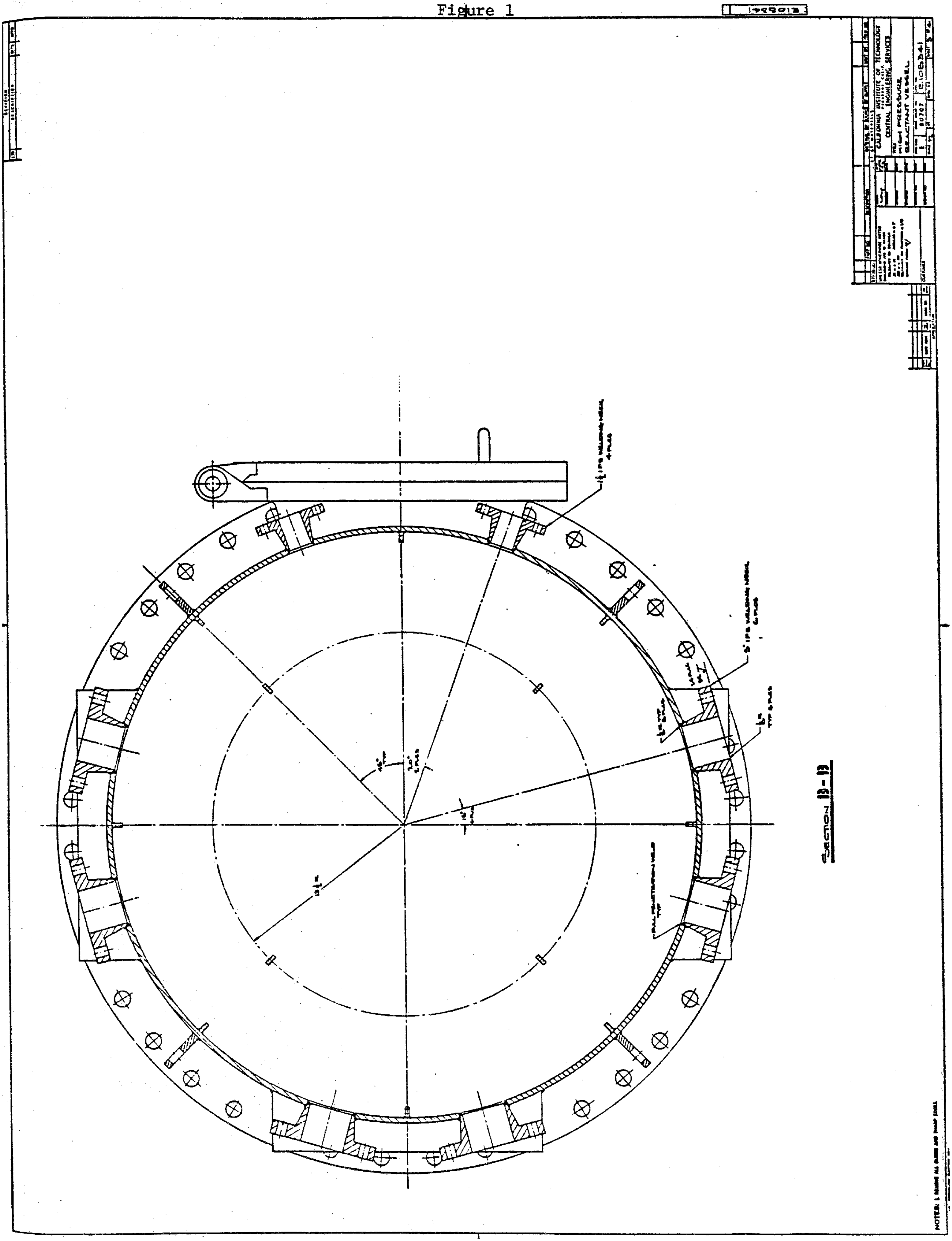
REACTANT VESSEL

Figure 1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HIGH PRESSURE REACTANT VESSEL
SECTION B-B

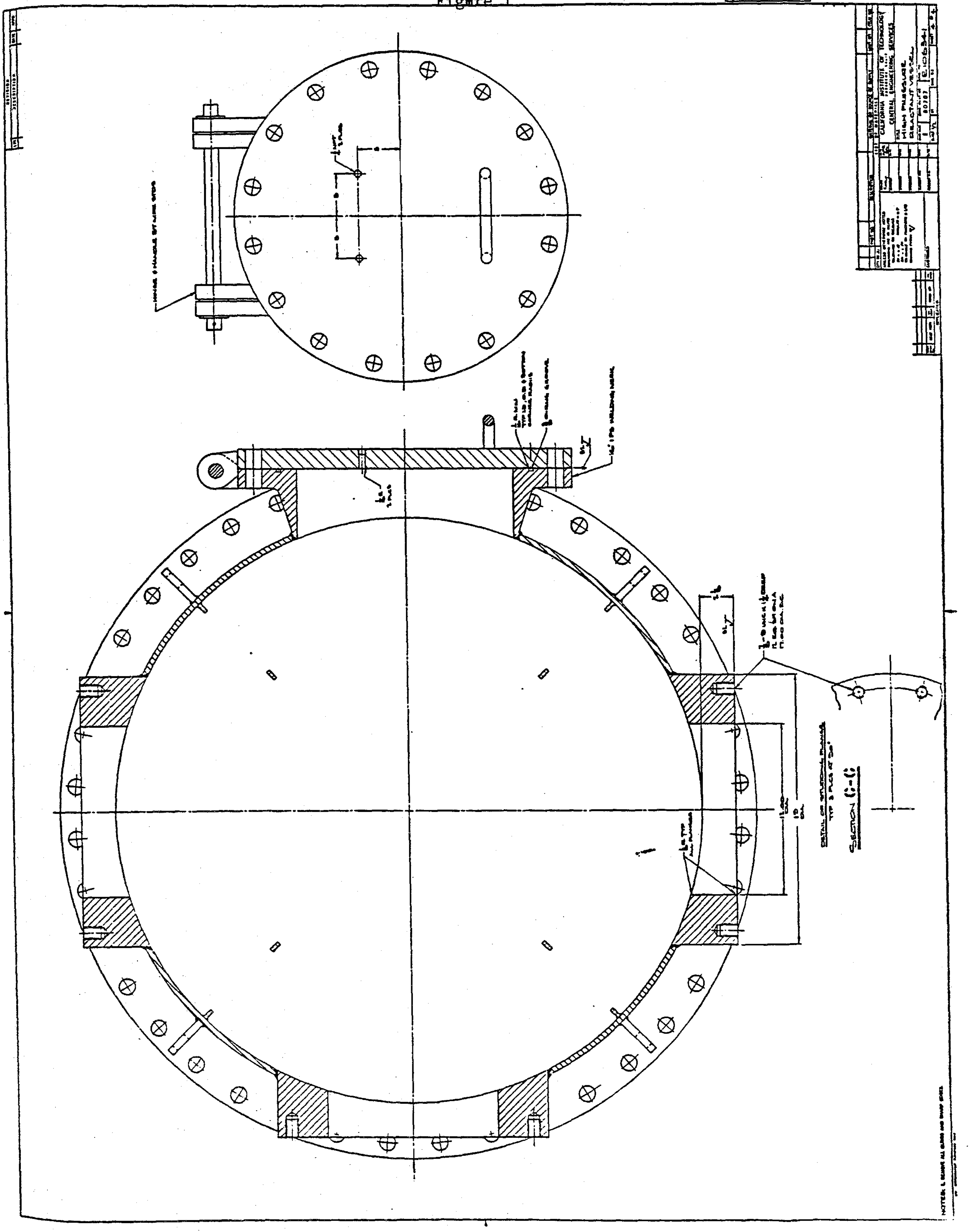
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Figure 1