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 d_o = 1/2 cm 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

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

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.

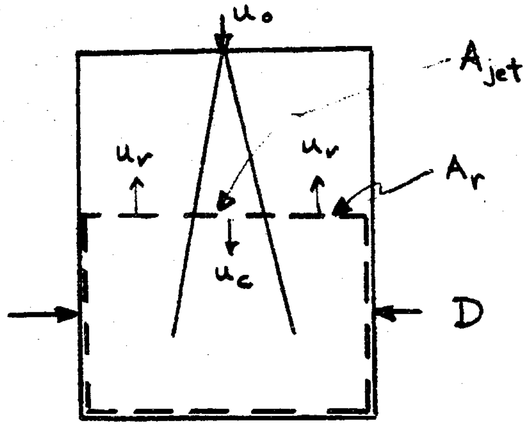
4.5. Control Panel / Gas Handling.

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

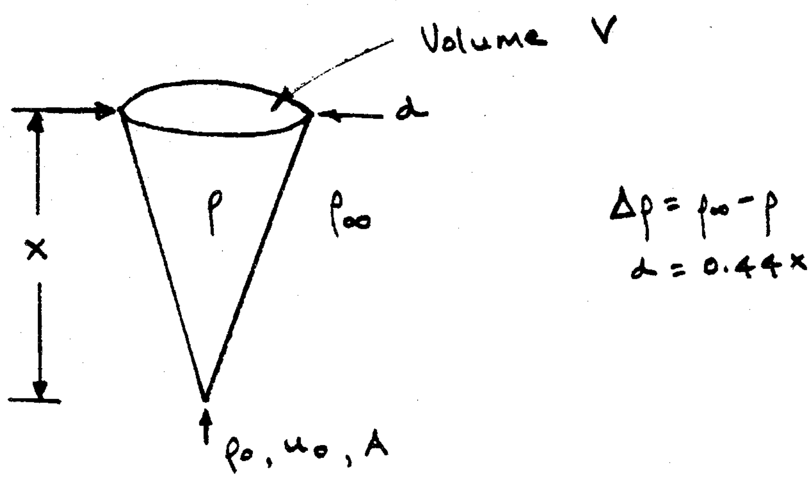
$D = 42$ inch $= 107$ cm

$d_o = 1/2$ cm

$x/d_o = 200$

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

Appendix 2: Buoyancy



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[illegible]

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.

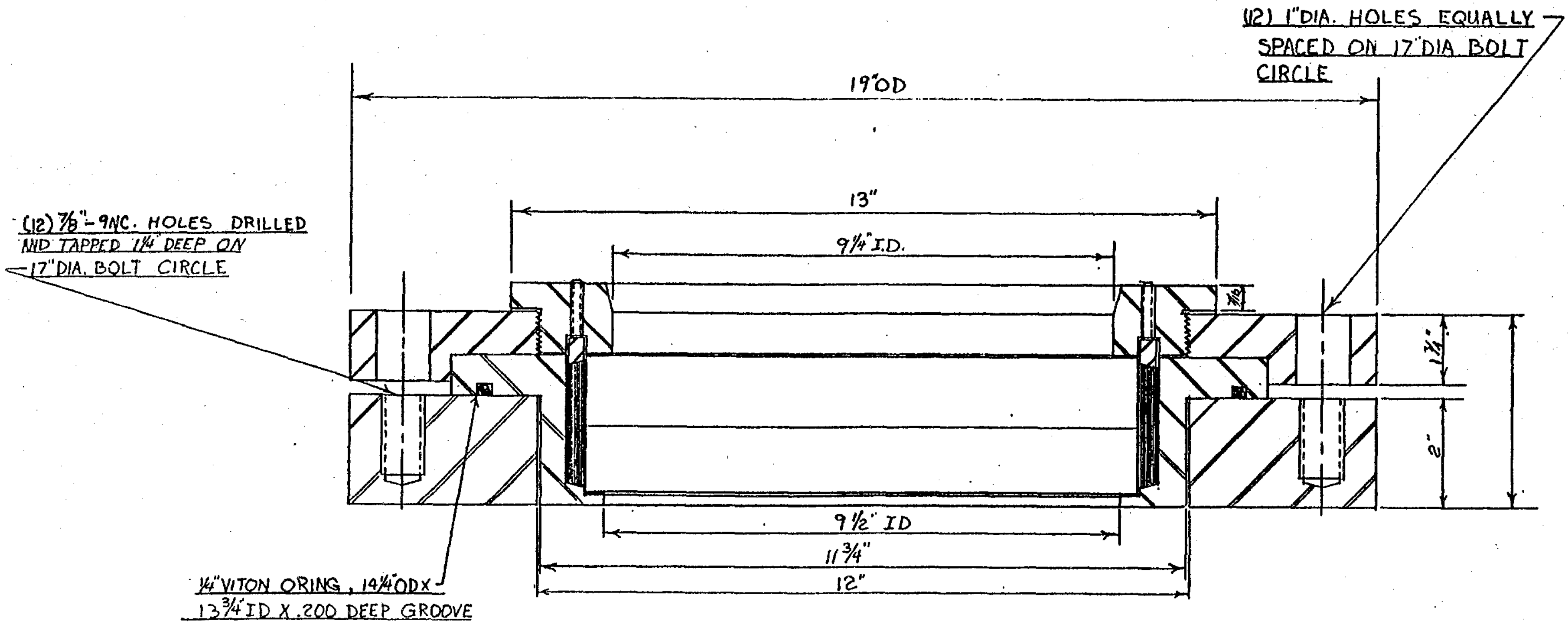
Sincerely yours,

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

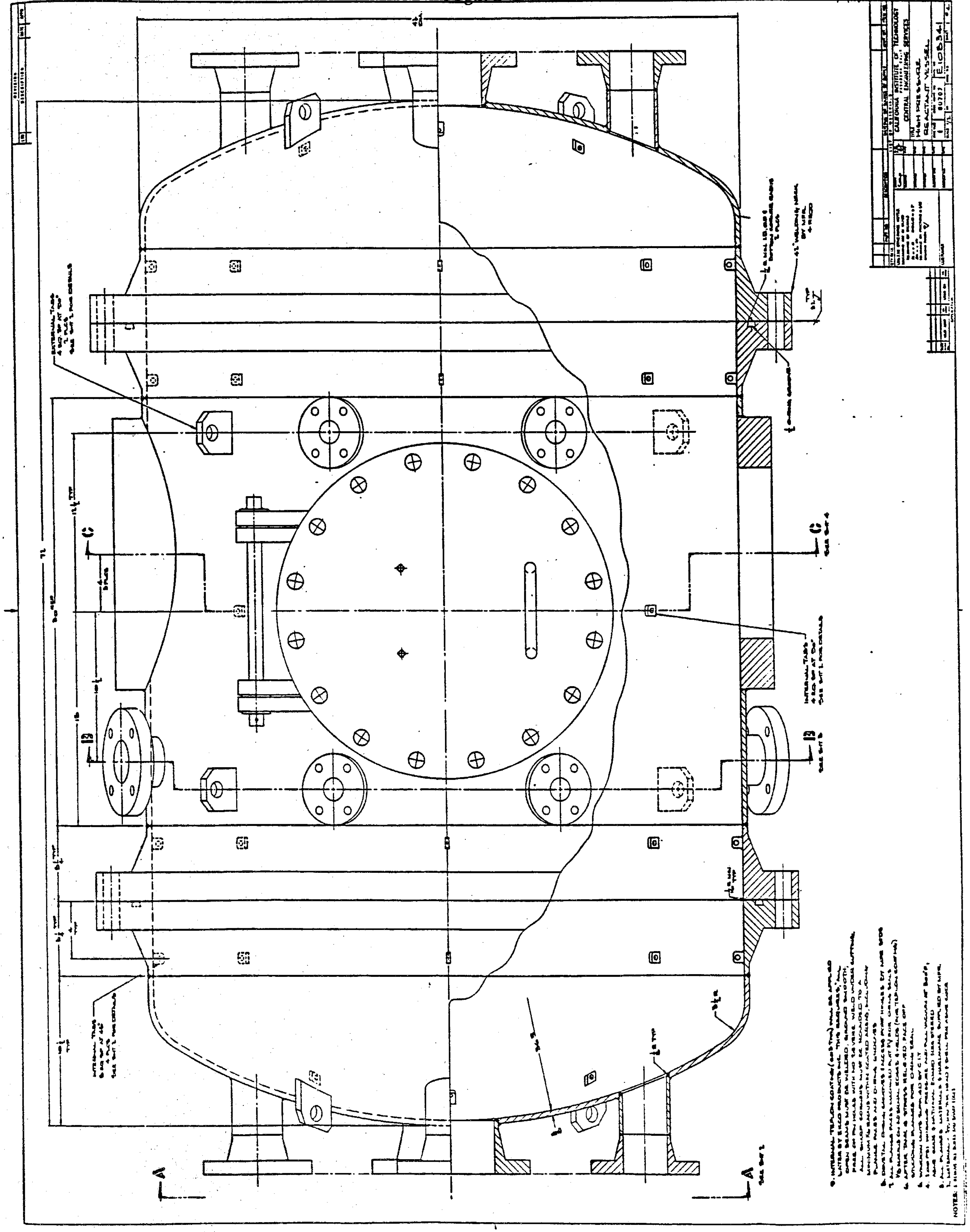

CALIFORNIA INSTITUTE OF TECHNOLOGY
CENTRAL ENGINEERING SERVICES
HIGH PRESSURE REACTANT VESSEL

Figure 1

Figure 1

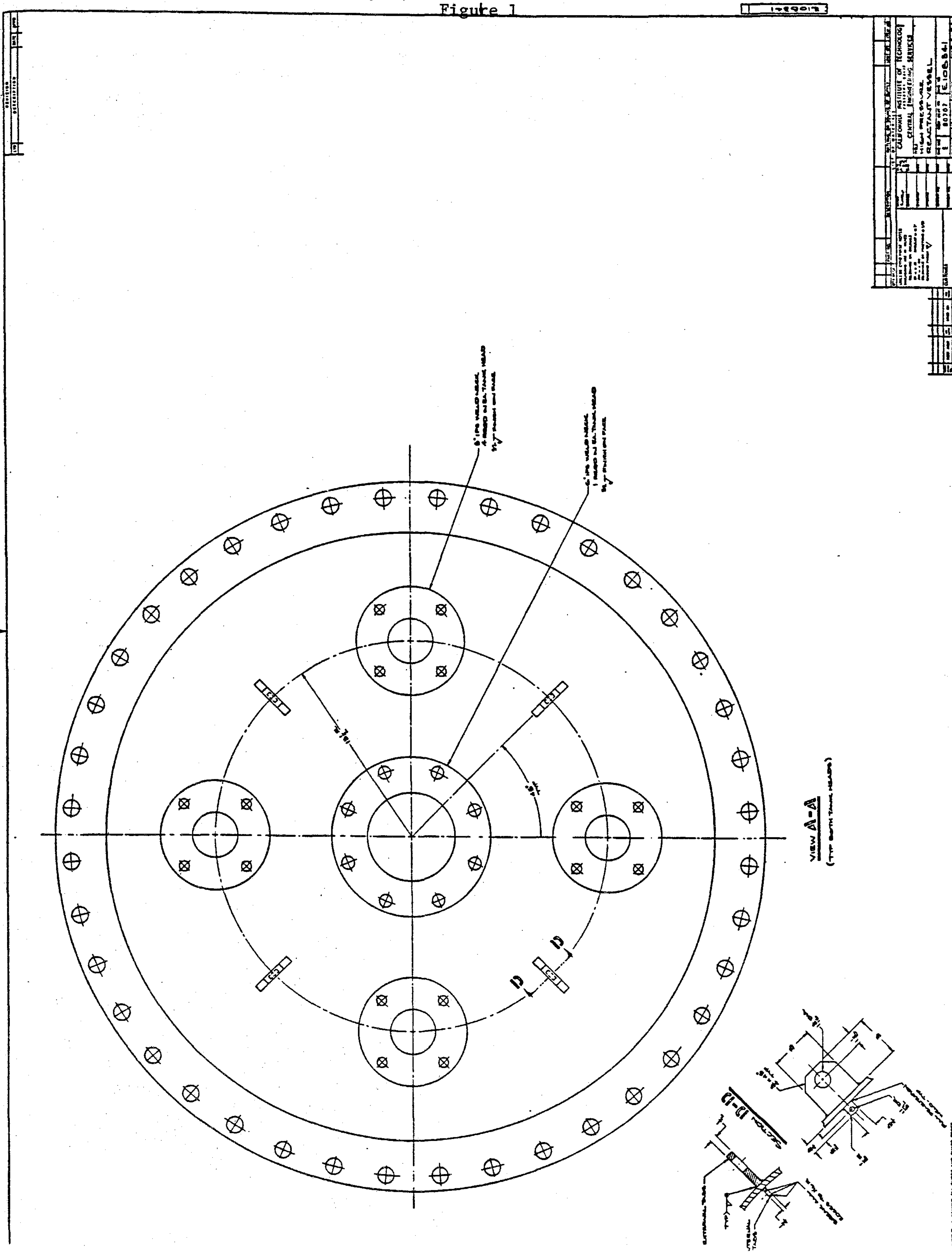

VIEW A-A
(TYP BOTH TANK HEADS)
CALIFORNIA INSTITUTE OF TECHNOLOGY
CENTRAL ENGINEERING SERVICES
HIGH PRESSURE
REACTANT VESSEL

Figure 1

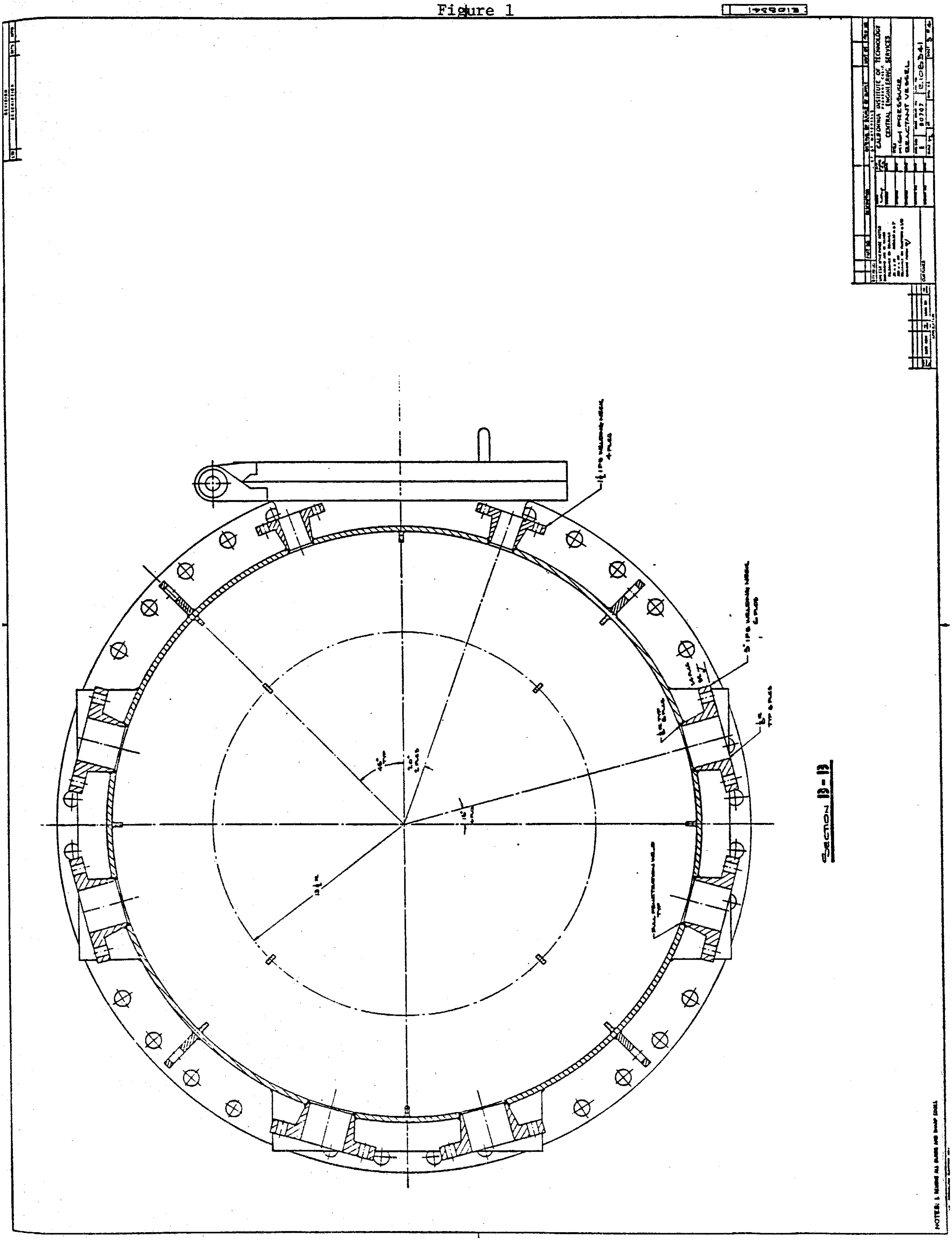
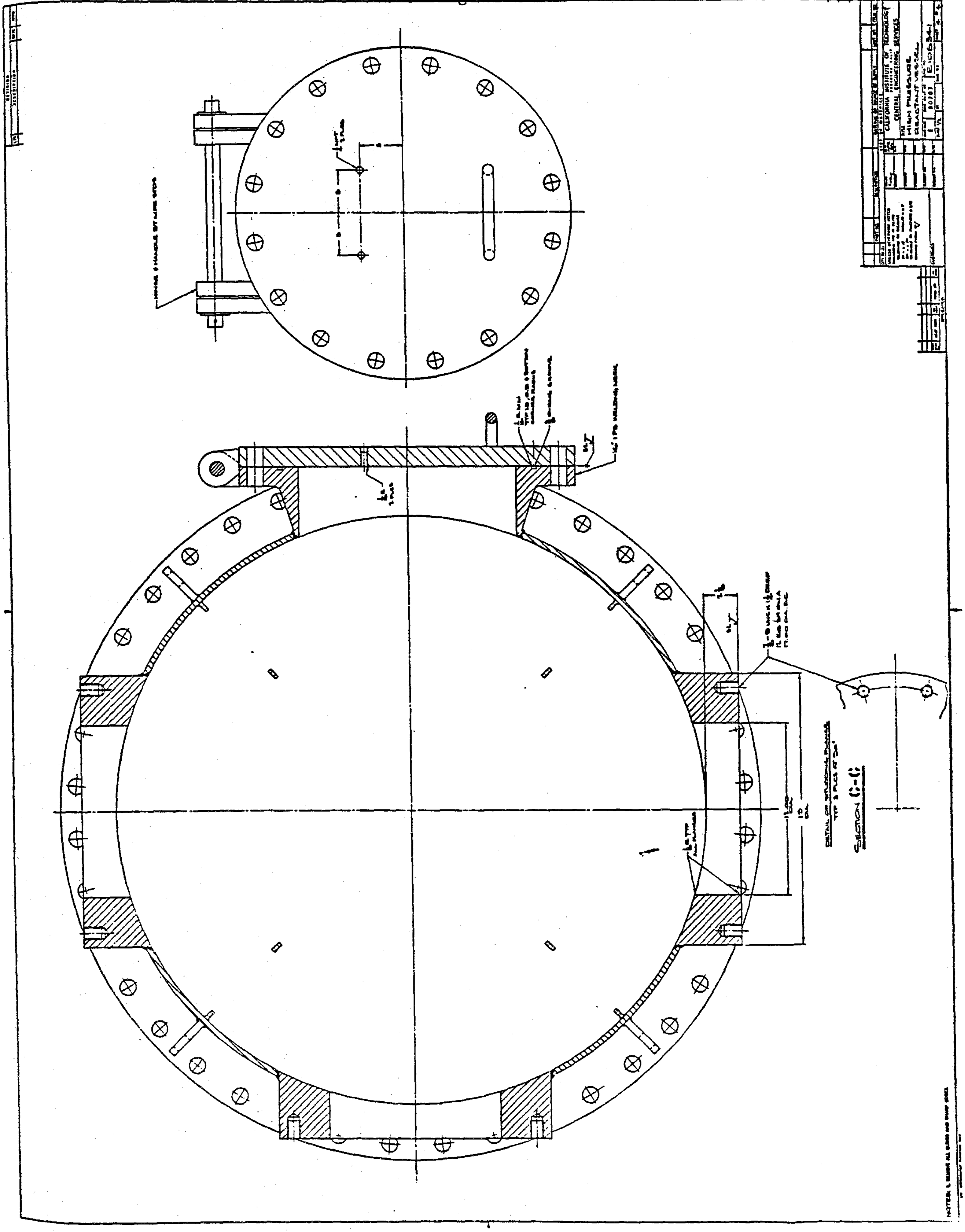

CALIFORNIA INSTITUTE OF TECHNOLOGY
CENTRAL ENGINEERING SERVICES
HIGH PRESSURE
REACTANT VESSEL
SECTION B-B

Figure 1



E10634-1
CALIFORNIA INSTITUTE OF TECHNOLOGY
CENTRAL ENGINEERING SERVICES
HIGH PRESSURE REACTANT VESSEL
E10634-1
SECTION C-C