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In this report, the feasibility of installing a new compressed gas driver at the existing BRL Shock Tube Facility is examined. The new driver would be three feet in diameter, 80 feet long, and would be installed in the space now occupied by the existing eight foot diameter driver. The new driver would be capable of holding an internal pressure of 1,760 psi and would be equipped with electric strip heaters to control the temperature of stored gas at 325 K to 650 K. A nitrogen gas pressurization system would be used with the new driver. The report concludes the facility modifications are feasible and outlines specific alterations which are needed. Construction costs were estimated to be about $1.1 million, and construction time was estimated to be 8 to 10 months.

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DESIGN CONCEPT FOR A LARGE SCALE TEST BED FOR LARGE BLAST/THERMAL SIMULATOR RESEARCH

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NOVEMBER 1987

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US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

DESTRUCTION NOTICE

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FOR
LARGE BLAST/THERMAL SIMULATOR RESEARCH

By
BLACK & VEATCH ENGINEERS-ARCHITECTS
KANSAS CITY, MISSOURI

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For

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PREFACE

The effort described in this report was performed as an outgrowth of a concurrent study to develop concepts for a Large Blast/Thermal Simulator (LB/TS). Construction of the large simulator has been proposed for testing the survivability of full scale military vehicles and other equipment under blast and thermal effects of nuclear weapons. The proposed simulator, if constructed, will be the largest such facility in the world in terms of physical dimensions and energy release capacity.

Performance criteria for the LB/TS imply a need for innovative real time flow control mechanisms. The size of the facility and the requirement that it be able to change blast overpressure and duration independently of one another make the use of conventional shock tube techniques expensive to employ. Conventional techniques using diaphragms to initiate the flow and changes in driver volume to control duration can be used, but real time flow control promise a more flexible and efficient facility at reduced cost. However, real time flow control in a blast simulator is an unproven concept. Because of the significant cost of an LB/TS facility, a high degree of confidence needs to be obtained in real time flow control mechanisms before they are used in its final design. Research into real time flow control mechanism could be performed at the BRL 2.44 meter shock tube at Aberdeen Proving Ground, Maryland, if certain modifications to the facility were carried out.

Needed modifications to the BRL facility are discussed in this document.

The study was conducted under funding by the SCIENTIFIC SERVICES PROGRAM as administered by Battelle Research Triangle Park Office, Dr. George G. Outterson, Program Manager. Technical guidance for the study was provided by Mr. Richard J. Pearson, U.S. Army Ballistic Research Laboratory.

SUMMARY

1. Feasibility. Modification of the BRL Shock Tube Facility on Spesutie Island for use as a Large Scale Test Bed for LB/TS Research is feasible.

2. Construction Cost. Facility modifications and procurement of a quick-valve and diaphragm mount will cost about $1,136,500.00 according to the following breakdown of costs:

Driver tube, repairs, heater:	$453,000.00
Quick-valve and supports:	$524,000.00
Diaphragm mounts:	$ 37,500.00
High pressure nitrogen system:	$122,000.00

3. Construction Time. Eight to ten months will be required to construct facility modifications and to procure a quick-valve and diaphragm mount.

4. Nature of Modifications. Recommended modification of the facility will include the following elements:

a. Reinforcement of the existing reaction pier.

b. Modifications to the existing shock tube to facilitate installation of the new driver.

c. Installation of a new three-foot diameter insulated driver, 80 feet long, and its anchorage to the reaction pier.

d. Upgrading of tracks supporting the new driver.

e. Erection of a temporary weather cover over the new driver.

f. Installation of a nitrogen pressurization system for the new driver.

g. Installation of electric strip heaters on the new driver and installation of an exhaust fan for its cool-down.

h. Installation of a liquid cooling system for the diaphragm and quick valve.

i. Addition of a panel in the Control Building for driver pressure/temperature control.

j. Modifications to the motor control center to accomodate the nitrogen system.

k. Removal of fixtures used in previous tests from the expansion section.

l. Removal of the existing diaphragm change platform from the reaction pier and addition of a materials handling system in its place.

m. Piping and wiring systems associated with modifications listed above.

5. Condition of Existing Tube. The thrust-resisting capacity of the reaction pier has diminished. It should be repaired prior to future use of the 2.44 meter driver, regardless of whether other recommendations in this report are or are not implemented.

6. Test Plan. A plan of testing to be performed at the modified facility should be developed in conjunction with its engineering design. A partial listing of test plan elements was identified in the study, as follows:

a. Pressure tests of the new driver and liquid nitrogen driver gas supply system.

b. Shakedown tests using heated drivers and diaphragms. Collection of information on stress history in the new driver tube.

c. Test to determine shock rise time as a function of distance down the expansion section and quick-valve opening time using heated driver gas.

d. Shock rise time experiments using a system containing both quick valves and diaphragms. (Note: necessary only if quick-valve opening rates do not produce short enough shock rise times.)

e. Test of the ability of quick-valve closure to control blast wave decay rates.

f. Rarefaction Wave Eliminator (RWE) tests at the downstream end of the facility using blast wave shapes produced by quick-valve closure.

SECTION 1

INTRODUCTION

1.1 AUTHORITY

This study was conducted under contract with Battelle Columbus Division, Contract No. DAAL03-86-D-0001. Technical guidance for the performance of the study was provided by the U. S. Army Ballistic Research Laboratory (BRL), Aberdeen Proving Ground, Maryland.

1.2 GENERAL DESCRIPTION

This report presents results of a study to develop a Design Concept for a Large Scale Test Bed for Large Blast/Thermal Simulator (LB/TS) Research. The Design Concept was based upon modification of the existing BRL 2.44 meter (8-foot diameter) shock tube facility at Aberdeen Proving Ground, Maryland. Elements of the study were:

a. An evaluation of the existing shock tube support system and existing railbed, particularly with respect to their capability to support additional loads.

b. An evaluation of the existing driver and reaction pier to determine their ability to support thrust loads of a new driver proposed for installation inside the existing driver.

c. Development of a design concept for a new high pressure heated driver.

d. Development of a concept for heating the new driver with an external electrical heating system.

e. Development of a concept for a cooled converging nozzle and double-diaphragm system.

f. Development of a method for transferring thrust from the new driver into the existing reaction pier and a determination of additions to the existing support system needed to carry the weight of the new driver.

g. Development of a concept for pressurization of the driver using liquid nitrogen.

h. Derivation of cost estimates and schedules for test bed.

1.3 BACKGROUND

The U. S. Army and the Defense Nuclear Agency are conducting research into the design and operation of a large-scale nuclear blast and thermal radiation simulator. Technological gaps have been identified in recent conceptual studies (Reference 1) of the large simulator, and these gaps represent constraints upon its cost-effective design. No facility is known to exist at which research can be performed to bridge technological gaps. However, the BRL 2.44 meter shock tube may be a candidate for such research if it is altered to suit test bed requirements. This study deals with the nature of required alterations at that facility.

SECTION 2

EVALUATION OF THE BRL 2.44 METER SHOCK TUBE

2.1 VISUAL INSPECTION

The BRL 2.44 meter tube went into service in 1967 but has been used infrequently during the past two years. The high level of testing conducted earlier and a 20-year exposure to the elements has brought about a degree of deterioration of the tube and its ancillary structures. Its condition was visually inspected in December of 1986, and observations of that inspection are noted below:

a. Rail Bed. The rail bed upon which the driver is carried has settled. The rail bed beneath the expansion section has also settled except for the length resting on the reaction foundation. The most obvious settlement has occurred immediately below tube carriage wheels and has been accompanied by flexure of rails at these locations. At some previous time, shims were installed on top of some carriages to offset the effects of this settlement on tube alignment.

b. Driver Section. The downstream end of the driver was checked for roundness over an 80-foot length. The tube was found to be virtually round along this length except for a 5/16-inch elongation of the vertical axis about 50 to 60 feet from the open end. This distortion is believed to be inconsequential. Straightness of the tube was checked against a stretched string; no flexure of consequence was apparent. The driver was not checked for levelness, although evidence at the rail bed and reaction pier suggests that the closed end has settled more than the open end. Walls of the driver were generally in good condition, however, an area of one-inch by two-inch size was noted where the outside fibers were delaminating from curved fibers beneath.

c. Reaction Pier. Moderate to severe cracking of concrete has occurred on both parts of the reaction pier. The most severe cracking radiates from anchor bolts on top of the pier. Settlement of the rail bed may have induced residual stresses on upper anchor bolts which, when combined with tube thrust loadings, caused these cracks. Cracks in the pier constitute an entry-way for moisture and a potential cause of rebar corrosion, although little corrosion of reinforcing was evident.

d. Reaction Foundation. The condition of the reaction foundation, including its connection to the reaction pier, appeared to be good. One exception to this is the tendency of water to pond in depressions in its top surface. The bottom connection of the driver is located in such a depression and is corroding from its exposure to ponded water. The reaction foundation is equipped with a subsurface drainage system which was not operating at the time of inspection. Alternating sump pumps which were intended to discharge subsurface groundwater have been turned off, reportedly, to conserve maintenance costs. Operability of pumps was confirmed during the inspection.

e. Expansion Section. Other than settlement of its rail bed, the expansion section showed no evidence of serious deterioration. Post-construction additions inside and on the downstream end were noted with respect to their effect on test bed concepts.

f. Site Selection for Nitrogen Equipment. Any of several locations on the north side of the Reaction Foundation was determined to be feasible for situating elements of the test bed nitrogen system.

2.2 EXAMINATION OF OPERATIONS LOG

Records of shock tube operations over the past nine years were examined. Logs showed that the driver pressure last exceeded 91 psi in 1977 (a 100 psi driver pressure was used in November of 1977). Table 2-1 shows a history of shock tube usage over the past five years.

TABLE 2-1

5-YEAR HISTORY OF SHOCK TUBE USAGE

YEAR	NO. OF SHOTS	MAX. DRIVER PRESSURE (PSI)	MAX. SIDE-ON PRESSURE (PSI)
1982	45	70	17.5
1983	32	91	20
1984	39	91	20
1985	4	91	20
1986	4	32.5	10

2.3 CONCLUSIONS

Consideration of evidence gathered during the field inspection brought about the following conclusions:

a. Suitability for Test Bed Construction. The 2.44 meter shock tube can be modified for use in test bed experiments.

b. Rail Bed. New temporary supports or concrete foundations should be placed under each of the 11 driver supports and under 5 of 6 expansion section supports. Precise survey should be used in conjunction with this construction to enable restoration of both sections to their original alignment (if permanent foundations are installed).

c. Driver Support System. Additional supports should be installed between existing driver supports if the test bed concept involves installation of the new driver inside the existing driver.

d. Expansion Tube Support System. Temporary shoring will be required beneath the expansion section if the test bed concept involves transport of the new driver inside the expansion section.

e. Reaction Pier. The resistance of the pier to driver thrust in its present condition is indeterminate but is known to be less than its original design value. Reinforcement of the pier will be needed to restore it to original strength. Instrumentation of the pier to determine its approximate strength is theoretically possible, but costs of instrumentation and data analysis will probably exceed costs of its restoration. Failure of concrete in diagonal tension has caused a redistribution of strength to steel reinforcing at several locations. Direct measurement of maximum tension and bond stresses in reinforcing steel is not possible.

A further complication in analysis of the pier is associated with settlement of the driver. That is, pier distortions caused by driver roadbed settlement will cause unequal distribution of thrust loads at the four tube attachments to the reaction pier.

f. Suitability for Continued Use of 2.44 Meter Driver. A determination of the maximum safe driver pressure in its existing condition was not part of the study. However, observations made during the field inspection suggest that it should be downgraded or not used at all in the future unless it is restored. Field observations included reaction pier damage as noted in the preceding paragraph, a localized area of driver shell damage, longitudinal stressing of the driver shell caused by unequal settlements of the driver roadbed and the reaction foundation, and welds to the driver shell at a test table inside the driver. Restoration would include repair of these four items and subsequent pressure testing.

SECTION 3

ALTERNATIVE METHODS FOR INSTALLATION OF THE NEW DRIVER

3.1 METHOD OF INSTALLATION

Several methods for installing the new driver in the existing facility were studied. The primary objective of this phase of the study was to minimize the combined costs of the LB/TS Test Bed modification and subsequent restoration of the 2.44 meter driver to operating condition. Restoration of the driver to its original strength is discussed in paragraph 2.3f. One consideration was to maintain the integrity of the existing 2.44 meter tube so that hydrostatic testing would not be necessary to put it back into service. After inspection of the existing tube, it was determined that hydrostatic testing will be needed to redefine its maximum working pressure, regardless of how the modification is done. The various methods considered for installing the new driver are shown in Figures 3-1 and 3-2, and are described in the following paragraphs.

3.1.1 Method I

Method I is referred to as the Muzzle Load concept. In this method, the new driver would be loaded into the downstream end of the existing expansion section. The new driver would be supported on flanged wheels which will roll on a temporary track. This track would extend from 80 feet outside to 80 feet inside the expansion section. The driver would be rolled 80 feet into the tube, and the outside track would then be moved into the tube through the opening at the diaphragm section. The opening at the diaphragm section will limit the length of track sections to 20 feet.

The driver would be moved 200 feet through the expansion section and 80 feet into the existing driver section. An 80 foot length of track would remain in the expansion section so that the new driver may be rolled out of the 2.44 meter driver for maintenance of the new heater and insulation systems. The existing shock tube must be supported from beneath to carry the new driver as it travels on the track inside (Figure 3-3). This can be accomplished with temporary supports where the track is to be temporary and with permanent supports for an 80 feet distance upstream and downstream from the reaction pier. Temporary supports can be substituted for permanent supports if eventual and economical restoration of the 2.44 meter tube is not a consideration. However, settlement of temporary supports would need to be periodically monitored during the Test Bed experiment.

3.1.2 Method II

Method II is similar to Method I except that an 85 foot length of the existing expansion section would be temporarily removed while the new driver is loaded directly into the existing driver. The 85 foot length of expansion section would then be replaced, and 80 feet of track would be installed inside it (for driver extraction and maintenance).

3.1.3 Method III

Method III involves the cutting of anchor plates from the existing driver, removing the concrete barricade at the head end of the driver, installing a 100 foot extension to the existing rail system, and rolling the entire 270 foot driver a distance of 100 feet from the existing reaction pier. The new driver would then be installed on the existing rails and anchored to the reaction pier. Maintenance of the new tube could be done in place, i.e., without moving it.

3.1.4 Method IV

In Method IV, an 85-foot section of the existing driver, starting at a point 25 foot upstream of the existing diaphragm flange, would be removed. The new driver would be installed on the vacated 85 feet of existing track and then rolled into the remaining 25-foot section of existing driver. It would be attached to the existing diaphragm flange. The new driver would be open for maintenance except for the 25 feet inside the existing driver.

3.1.5 Method V

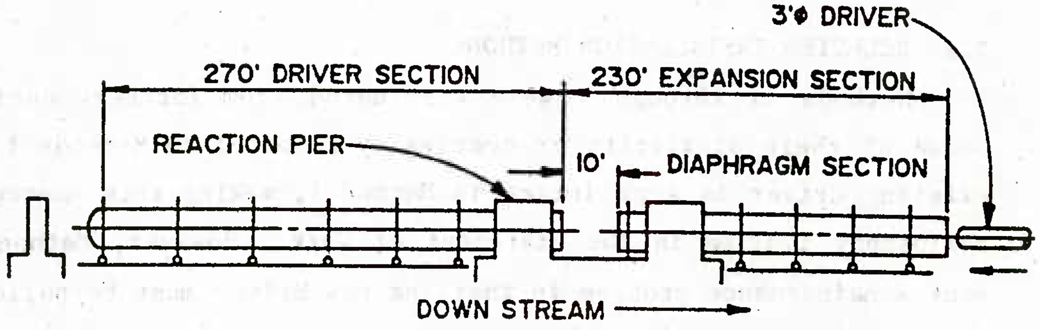
In Method V, the entire 270-foot existing driver would be removed without cutting either the tube wall or the anchor plates. The new driver would be installed in place and anchored to the reaction pier. Maintenance could be accomplished without moving the new driver.

3.1.6 Method VI

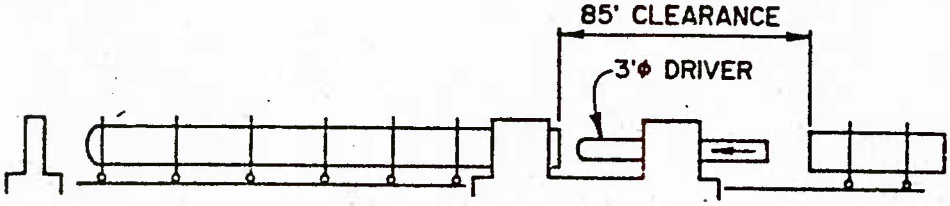
Method VI is similar to Method V except only an 85-foot section of existing driver would be removed. The 2.44 meter tube would be cut 85 feet upstream from the diaphragm flange and lifted off the track and reaction pier and set to one side on blocks.

3.2 SELECTED INSTALLATION METHODS

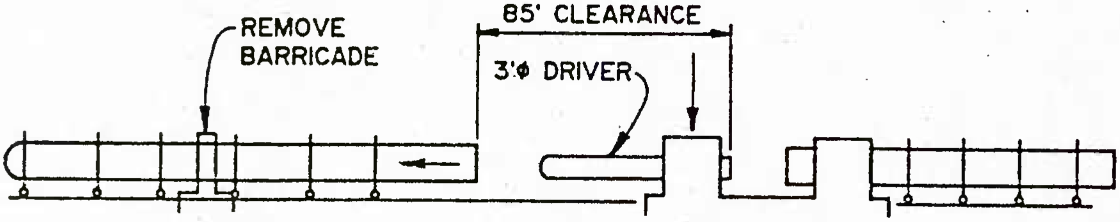
Methods II through V were eliminated from further consideration because of their similarity or complexity compared to Methods I and VI. The existing driver is kept intact in Method I, making this concept conform to philosophy implied in the Statement of Work. However, Method I will present a maintenance problem in that the new driver must be pulled out of the existing driver and into the expansion section to replace electric heaters. This undesirable feature of Method I led to a more detailed study of Method VI. Both methods are considered in the succeeding sections of this report.



METHOD I - MUZZLE LOAD, NO CUT



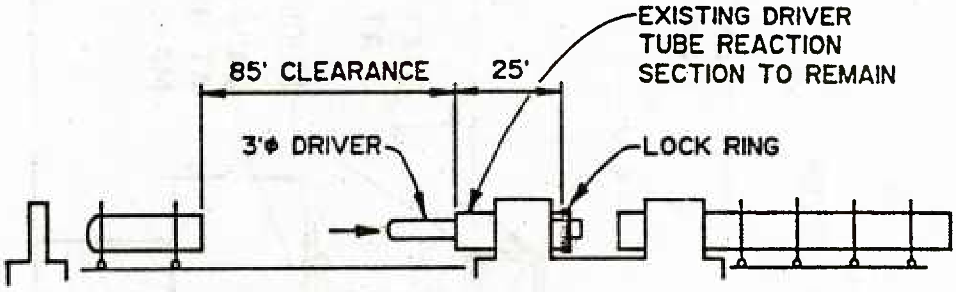
METHOD II - CUT EXPANSION TUBE FOR BREECH LOAD



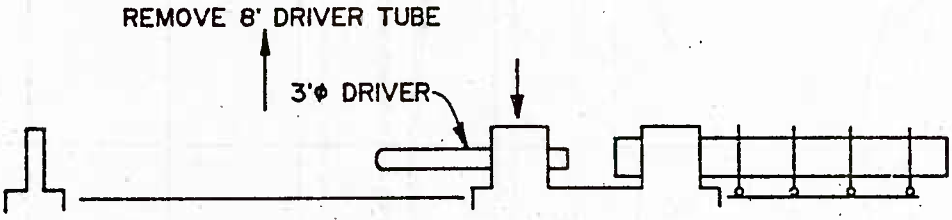
METHOD III - CUT DRIVER ANCHOR PLATES & MOVE

DRIVER INSTALLATION
METHODS I, II, & III

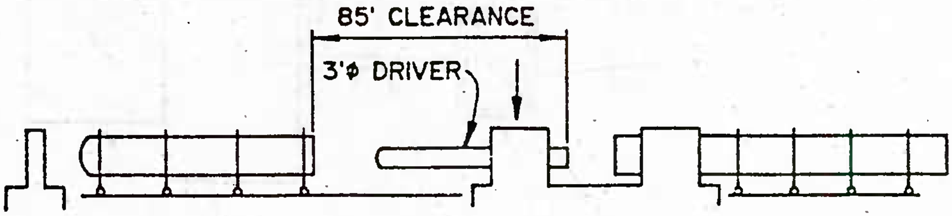
Figure 3-1



METHOD IV - CUT DRIVER TUBE FOR BREECH LOAD



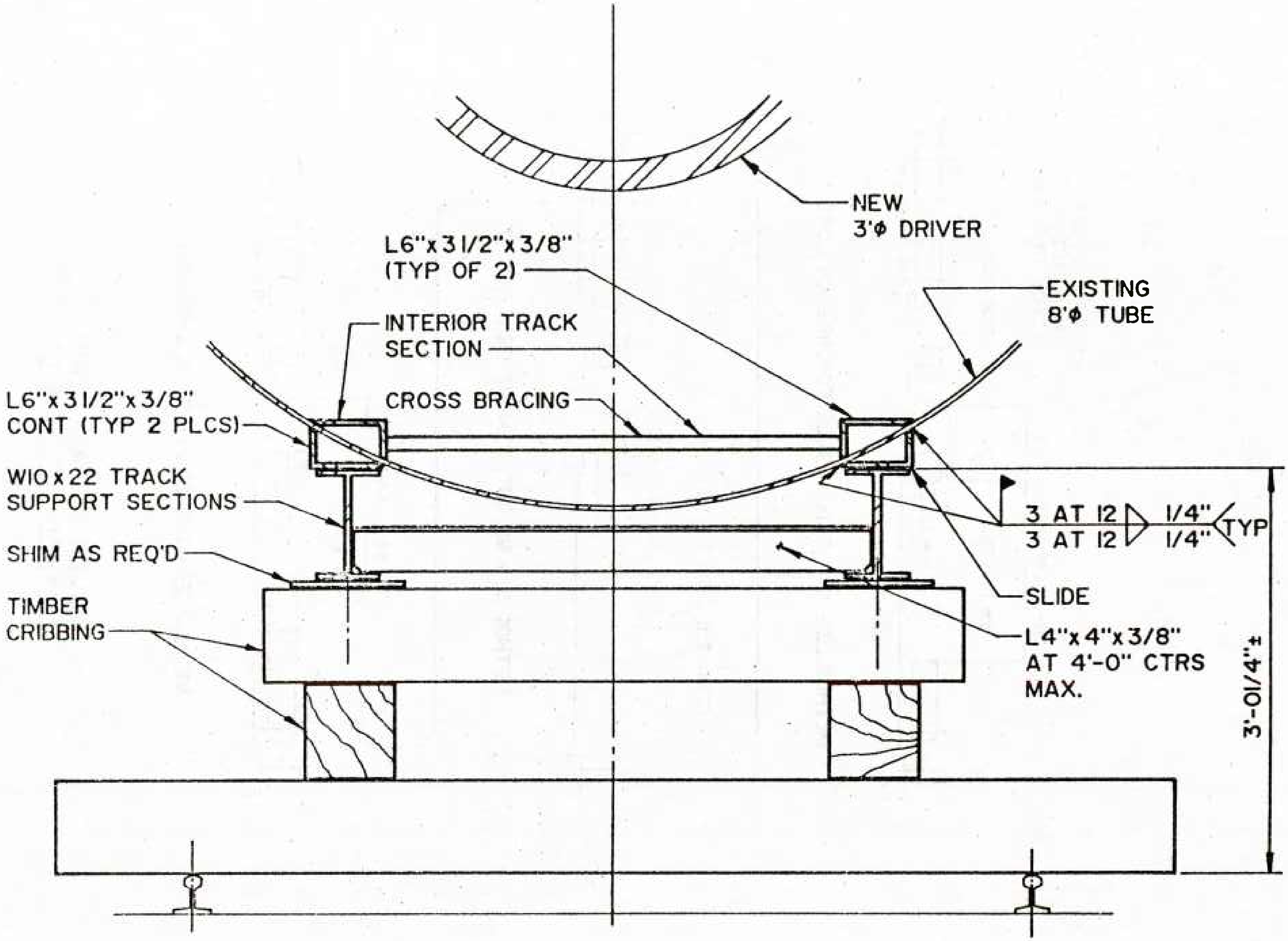
METHOD V - NO CUT, REMOVE DRIVER TUBE



METHOD VI - CUT DRIVER TUBE & REMOVE

DRIVER INSTALLATION
METHODS IV, V, & VI

Figure 3-2



TUBE SHORING - METHOD I

Figure 3-3

SECTION 4

NEW HIGH PRESSURE DRIVER

4.1 DRIVER SIZE AND MATERIAL

The new high pressure driver will have an overall length of 80 feet and an inside diameter of 36 inches. The driver shell will be constructed of SA 516 Grade 70 steel and will be 2.25 inches thick. A 36-inch inside diameter flange, rated at 1500 psi class, will be mounted on the downstream end to connect either the converging nozzle or a quick valve. This flange will withstand 2665 psi at 700 F. The upstream end of the driver will be closed with a welded hemispherical head. A 12 inch diameter flange connection is welded to the hemispherical head to provide a means for air cooling the driver.

4.2 DRIVER SUPPORT

Two methods of driver tube support were developed to suit two alternative means (Methods I and VI) of driver installation. If the driver tube is installed inside the existing 2.44 meter diameter driver, the support shown in Figure 4-1 should be used. If the existing driver is removed from the reaction pier to facilitate the new driver, the support shown in Figure 4-2 should be used. Supports shown in Figure 4-2 would in turn be supported by new track supports (See Figure 4-3). These track supports should be installed at 10-foot intervals and will permit re-installation of the 2.44 meter driver upon conclusion of LB/TS test bed experiments. As noted previously, temporary supports can be substituted for permanent supports if eventual and economical restoration of the 2.44 meter tube is not a consideration.

4.3 DRIVER ANCHOR

The new driver can be anchored to the existing reaction pier in either of two ways, depending upon whether the existing driver is or is not removed. If the new driver is located inside the existing 2.44 meter driver, its flange should be bolted to a 12-inch thick plate which is also bolted to the existing driver flange. The converging diaphragm section and quick valve can be bolted to another flange which is welded to an extension of the driver on the downstream size of the 12-inch thick plate (See Figure

4-4). This intricate configuration was derived to permit hydrostatic testing of the new driver in the shop and its subsequent insertion into the muzzle of the existing expansion section (or upstream from the existing reaction pier).

If the 2.44 meter driver is removed from the reaction pier, a 5-foot thick concrete block can be attached to the downstream side of the reaction pier as shown in Figure 4-5. The block would have a hole in it to allow the new driver to pass through, and the driver can be anchored by a split ring on the downstream side of the concrete block as shown in Figure 4-6.

The first of these two methods lends itself to relative ease of restoring the 2.44-meter driver to operating condition. Regardless of the method used, reinforcement of the Reaction Pier (See Figure 4-7) will be required. Replacement of fractured concrete and epoxy-injection of cracks will be needed before reinforcement of the pier.

4.4 MAXIMUM OPERATING THRUST WITH NITROGEN

The magnitude of thrust developed by the driver depends on whether or not a divergent diffuser is attached to the discharge nozzle. With a diffuser, the maximum thrust estimate is 818,000 lbs as outlined in the scope of work. Such a diffuser was only considered to account for a very unlikely future contingency. That is, the driver is expected to operate without diverging nozzle. An effort was made to evaluate the built-in safety factor included in the conceptual design when the driver operates in the expected configuration including the transient effects due to the rarefaction waves.

After the sudden removal of the throat diaphragm the driver gas accelerates and reaches the limiting throat exit velocity or critical choked flow. In the process rarefaction waves move upstream into the driver gas. This gas is thus accelerated by the waves and by passage through the convergent. As soon as the rear of the wave clears the convergent the two modes of acceleration are separated and the only unsteady part of the flow is the spreading wave in the driver. Otherwise the flow can be treated as one-directional and adiabatic everywhere at least until the front wave reaches the driver head.

The wave equation (Re: Shapiro Eq. 25.32d) relates the flow to the initial rest properties of the gas ahead of the wave as follows:

$$Mb = a(1-b) \qquad (1)$$

Where: M = Local Mach number

$a = 2/(k-1) = 5$

b = Ratio of local to initial acoustic velocity

$k = 1.4 = 7/5$ for nitrogen

In the time frame selected there is no acceleration between the rear of the wave and the convergent inlet. The Mach number M at the rear of the wave is the inlet Mach number of the 4:1 area ratio convergent and verifies (Re: Shapiro Eq. 4.19):

$$4M = [(1 + M^2/a)(5/6)]^3 \qquad (2)$$

The subsonic root of this equation is by iteration:

$M = 0.146548$

Hence: $b = 0.971525$

Based on the isentropic relations (Re: Shapiro Eq. 4.12) the ratio of other flow properties at the rear of the wave relative to the initial value ahead of the wave are equal to a power n of b as follows:

$n = 2$ for temperatures

$n = a = 5$ for densities

$n = ka = 7$ for pressures

The time rate increase G of driver gas momentum due to the wave is then computed by integration from the front (b=1) to the rear (b=b) of the wave as:

$$G/PA = 1 - b^7 - 35b^5(1-b)^2 \qquad (3)$$

Where: P = initial driver gas absolute pressure

A = driver gas cross section

It may be shown that the last two terms of this equation are respectively the dimensionless convergent inlet pressure force (H/PA) and influx momentum (K/PA) in that order.

$$H = .816916 \ (PA)$$
$$K = .024462 \ (PA)$$
$$G = .158522 \ (PA)$$

The convergent inlet impulse function F is by definition the sum of H and K or:

$$F = .841478 \ (PA)$$

In the convergent there is no further change to the stagnation properties of the rear of the wave. In particular, the convergent ratio of stagnation to local temperature is proportional (Re: Shapiro Eq. 4.14a) to:

$$1 + M^2/a$$

For choked throat conditions ($M = 1$) this ratio is at the throat:

$$1 + a^{-1} = 6/5 = (1/2)(k+1)$$

The ratio of outlet to inlet temperature was shown to be the square of the corresponding acoustic velocity ratio B so that (Re: Shapiro Eq. 6.24):

$$B^2 = (5/6)(1+M^2/a) \tag{4}$$

The ratio of throat to initial temperature is then by eliminating M between (1) and (4), equal to:

$$(bB)^2 = (5/6)[b^2+5(1-b)^2] \tag{5}$$

Or: $(bB) = .8887795$

As a result, applying the isentropic relations as before it may be shown that, in terms of the initial static pressure force PA, with K* the convergent efflux momentum, H* the throat pressure force, and F* the throat impulse function:

$$K^*/PA = (k/d)(bB)^7$$

$$H^*/PA = (1/d)(bB)^7$$

$$F^*/PA = (1/d)(k+1)(bB)^7$$

Or:

$$H^* = .109521\ (PA)$$

$$K^* = .15333\ (PA)$$

$$F^* = .262851\ (PA)$$

The momentum equation applied to the gas volume of the convergent (Re: Shapiro Eq. 4.21) shows that the net force R exerted by the gas on the convergent walls is in the direction of the flow and equal to the impulse function gradient:

$$R = F - F^* = .578627\ (PA)$$

Before the release of the diaphragm this force was equal to PA. There is thus a sudden drop of (PA-R) in the longitudinal wall tensioning load of about 42 percent. This is the first of a series of events discussed in Section 4.5 "LONGITUDINAL DYNAMIC EFFECTS".

The momentum equation applied to a control volume enveloping the driver states that the net external force S restraining the driver is in the direction of the flow and equal to the time rate increase G of momentum within the driver plus the excess of the outgoing momentum flux over the incoming momentum flux (here equal to zero).

Let p be the ambient absolute pressure at the head of the driver and p' the ambient absolute pressure at the tail of the driver outside of the choked discharge jet. The ratio of the annular base area outside of the jet to that of the throat is (d-1) = 3 and:

$$\begin{aligned} S &= G + K^* + H^* - pA + p'(A/d)(d-1) \qquad (6) \\ &= PA - R - pA + (3/4)p'A \\ &= [1 - (R/PA) - r + (3/4)r'](PA) \end{aligned}$$

By definition the magnitude of the driver thrust is equal to S but in the opposite direction. In the preceding equation $r = p/P$ and $r' = p'/P$. Since the backpressure p' never exceeds p, the last term is a drag as it reduces S. Zero backpressure is therefore not a conservative assumption. Instead let $r' = r = 14.7/1775 = .0082$ then:

$$S = [1 - (R/PA) - (r/d)](PA)$$
$$= 0.419303\ (PA)$$

For $P = 1775$ psia and $A = 1017.87\ \text{in}^2$,
$S = 757{,}567$ lbs

This is 92.6 percent of the 818,000 lb thrust in the scope of work.

4.5 LONGITUDINAL DYNAMIC EFFECTS

An effort was made to determine the magnitude of the longitudinal dynamic stress of the driver, based on test data acquired in 1966 for the design of the existing eight foot driver. These data are contained in a document entitled, Study of Shock Tube Driver Section Stresses and Expansion Reaction Section Loadings (Reference 3). The 40 millisecond trace of the longitudinal stress and the shock pressure downstream of the driver is included in Appendix B with the harmonic analysis of the longitudinal stress.

The harmonic analysis was done to determine the fundamental natural frequency of the driver tested. The length of the driver was one-half of its fundamental wavelength when both ends were free and one-quarter wavelength when one end was fixed and the other free. A 270 foot long driver anchored at one end is expected to resonate at 16 Hz. To detect such low frequency, at least one full period or 64 milliseconds of the signal must be sampled. Since the record covered less than 40 milliseconds, the 16 Hz signal could not be detected.

The record indicated that the longitudinal stress of the tested driver briefly exceeded the initial static stress by a factor of 1.62. This occurred approximately 10 milliseconds after the onset of dynamic conditions. This is less than the doubling of stresses that would occur if the driver anchor were instantaneously loaded by the static pressure on the driver head from a state of zero stress.

In the tested driver, the diaphragm area was equal to that of the driver cross section. The proposed Test Bed driver will be designed for a sonic throat of reduced area.

In the preceding Section 4.4 it was shown that firing the diaphragm causes a sudden reduction from PA to R in the tension load of the driver walls due to the internal gas pressure. This unloading, however, is of short duration since the restraining driver anchor will ultimately prevent the axial movement of the driver under its internal unbalanced pressure and jet thrust developed by the choked discharged gas.

Two factors must be considered, the reloading rate and the anchor location at the rear of the cylindrical driver section. With less than

1/16 inch play in the anchor bolt holes the reloading must indeed be considered instantaneous. This is the worst case as it generates elastic waves in the wall thus adding stresses that will peak at twice the tension that would otherwise result from the gradual application of the reload. No such problem would exist if the anchor had been located at the head of the driver for in that case the walls would be compressed instead of tensioned by the restraining force $S = sPA$ of the anchor.

The initial wall tension is $(1-r)\ PA$. Upon firing the diaphragm and as long as the anchor does not reload the wall tension drops to:

$$R-3p'A/4 = (1-r-s)\ PA$$

The sudden reload of the anchor is equivalent to a 2S static reload on the walls and the tension will then peak at $(1-r+s)\ PA$. The ratio of peak to initial wall tension is with $s = .4193$ and $r = .0088$:

$$1 + s/(1-r) = 1.4228$$

The allowable longitudinal stress is the same as the allowable hoop stress. However, the geometry of the cylindrical driver results in hoop stress being double the longitudinal stress under static conditions. In other words, the longitudinal wall stress may safely be allowed to exceed by up to 100 percent its initial static value. The 42.28 percent calculated above is thus intrinsically safe and does not require a thickness increase of the driver walls.

For flanged driver there is no such built in allowance and both flanges and bolts must be designed to withstand the dynamic maximum stress. It must be noted that some codes allow 25 percent increase in the allowable stress for loads of short duration.

The test driver thickness is 2.25 in. with .05 in. for corrosion allowance or a net thickness $t = 2.2$ in. Its radius $R' = 18$ inches. The gage design pressure $P' = 1760$ psig. The ASME Boiler Code, Section VIII, Longitudinal Stress is then:

$(P'/2t)(R'-0.4t) = 6848$ psi

At peak this stress may reach:

$(1.4228)(6848) = 9743$ psi

With a 16.5 feet maximum between supports, the bending stress was calculated to be 102 psi and the maximum operating longitudinal stress will not exceed:

$9743 + 102 = 9845$ psi

The maximum allowable stress with SA 516 steel, Grade 70 at 710 F is 16,240 psi. The safety factor is thus:

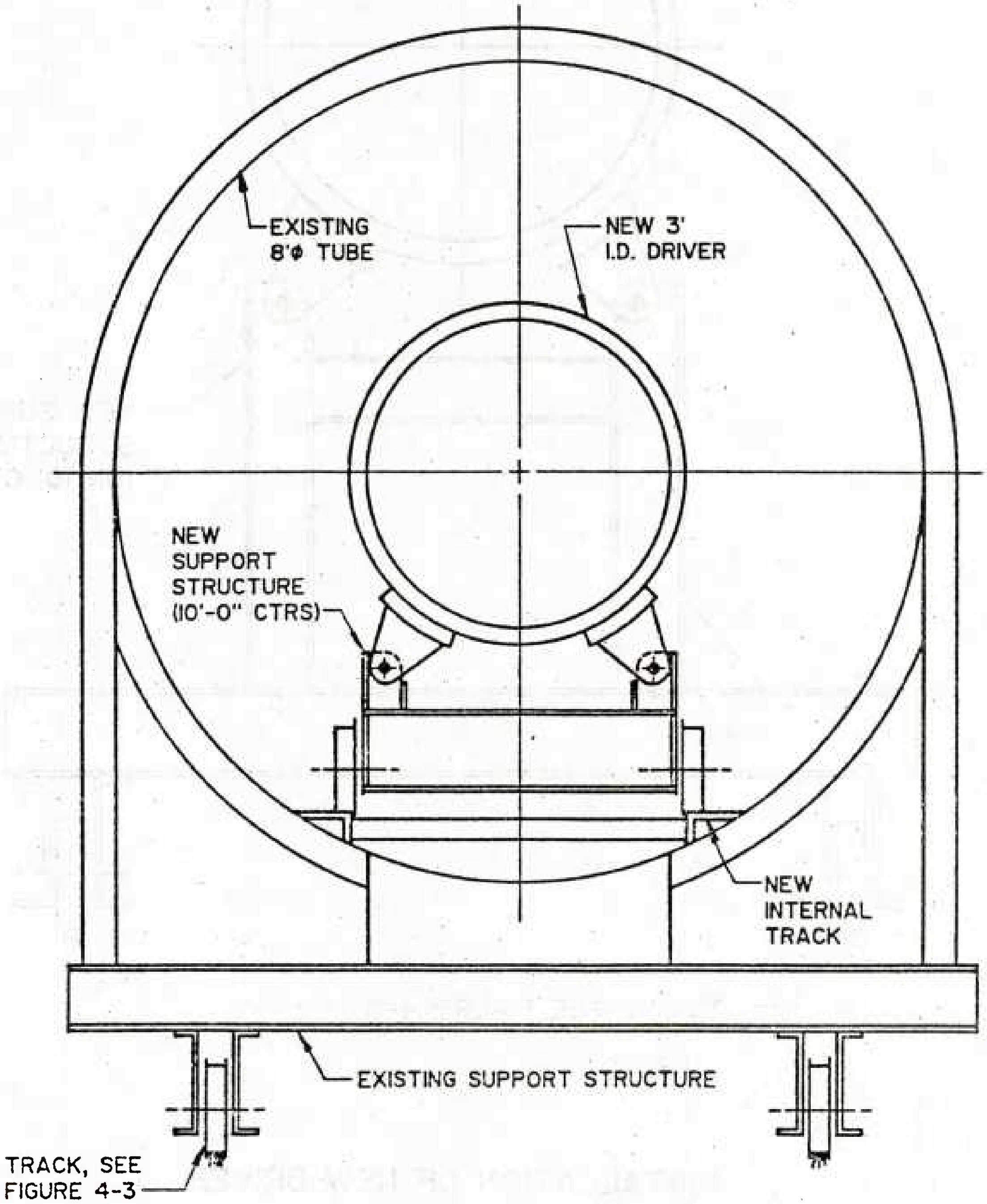
$16240/9845 = 1.6495$

The hoop stress is per ASME Boiler Code, Section VIII:

$(P'/t)(R'+0.6t) = 15456$ psi

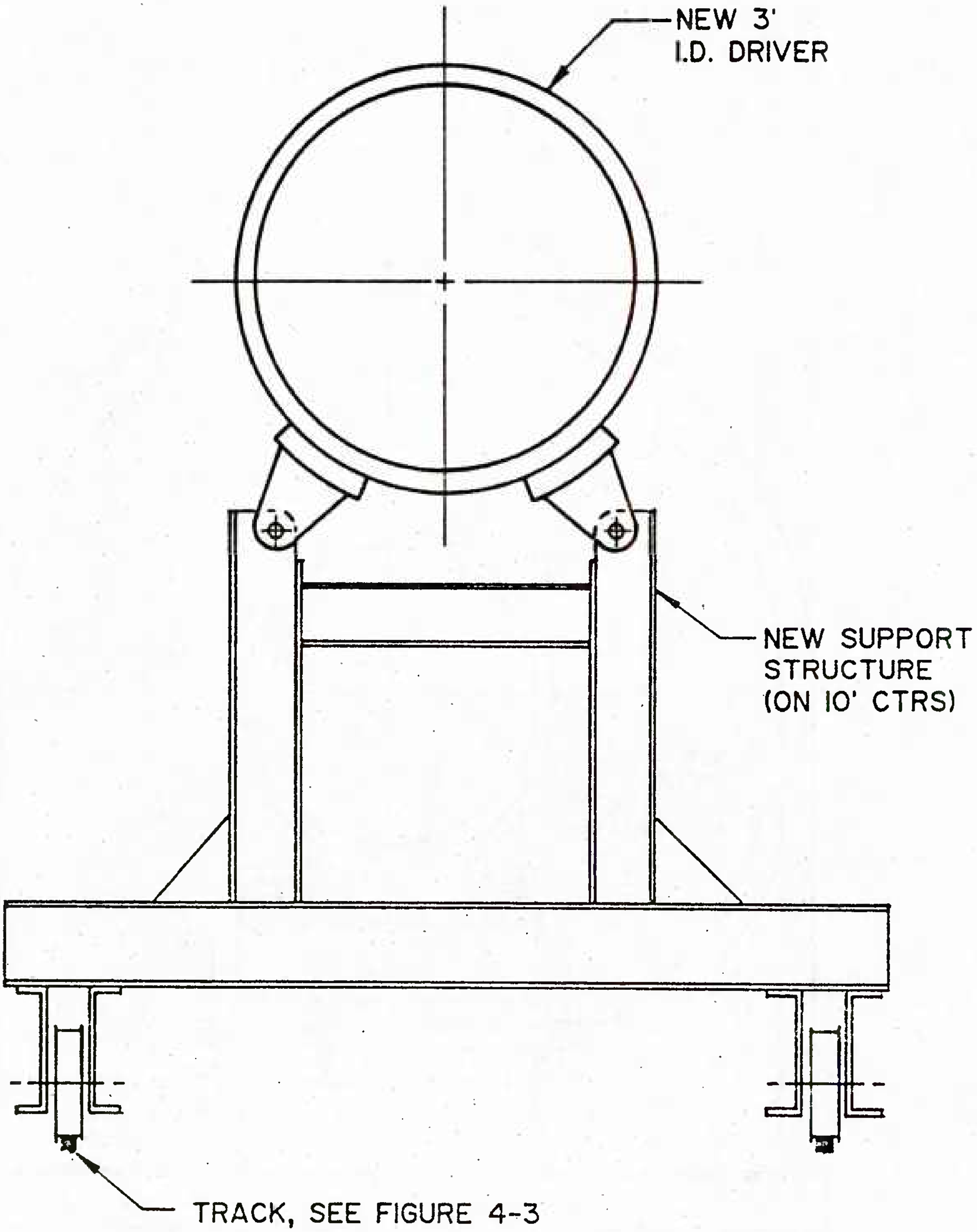
This is less than the 16240 psi allowable.

Computations of longitudinal dynamic effects are also included in Appendix B.



INSTALLATION OF NEW DRIVER
IN EXISTING TUBE

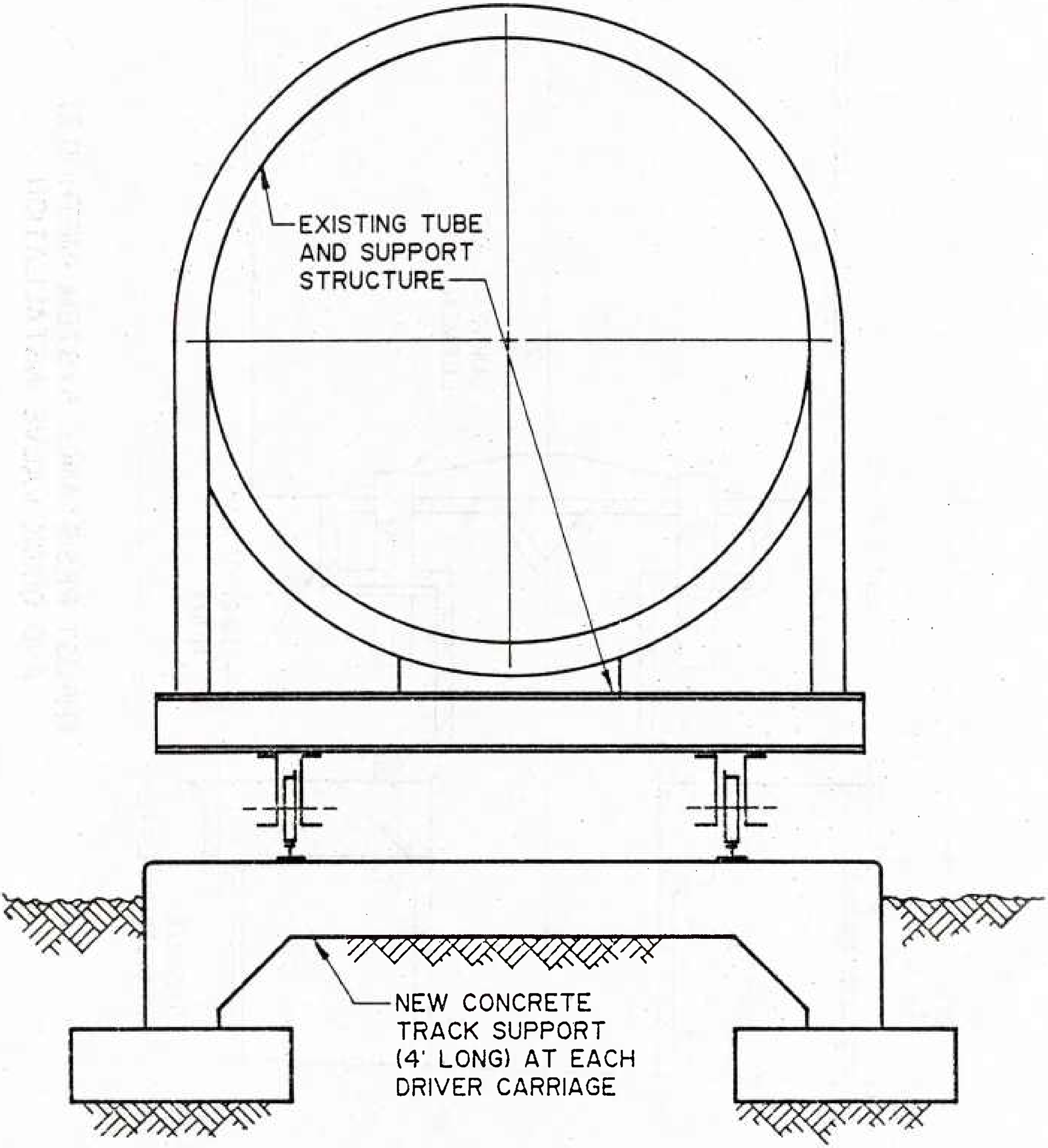
Figure 4-1



INSTALLATION OF NEW DRIVER
OUTSIDE EXISTING TUBE

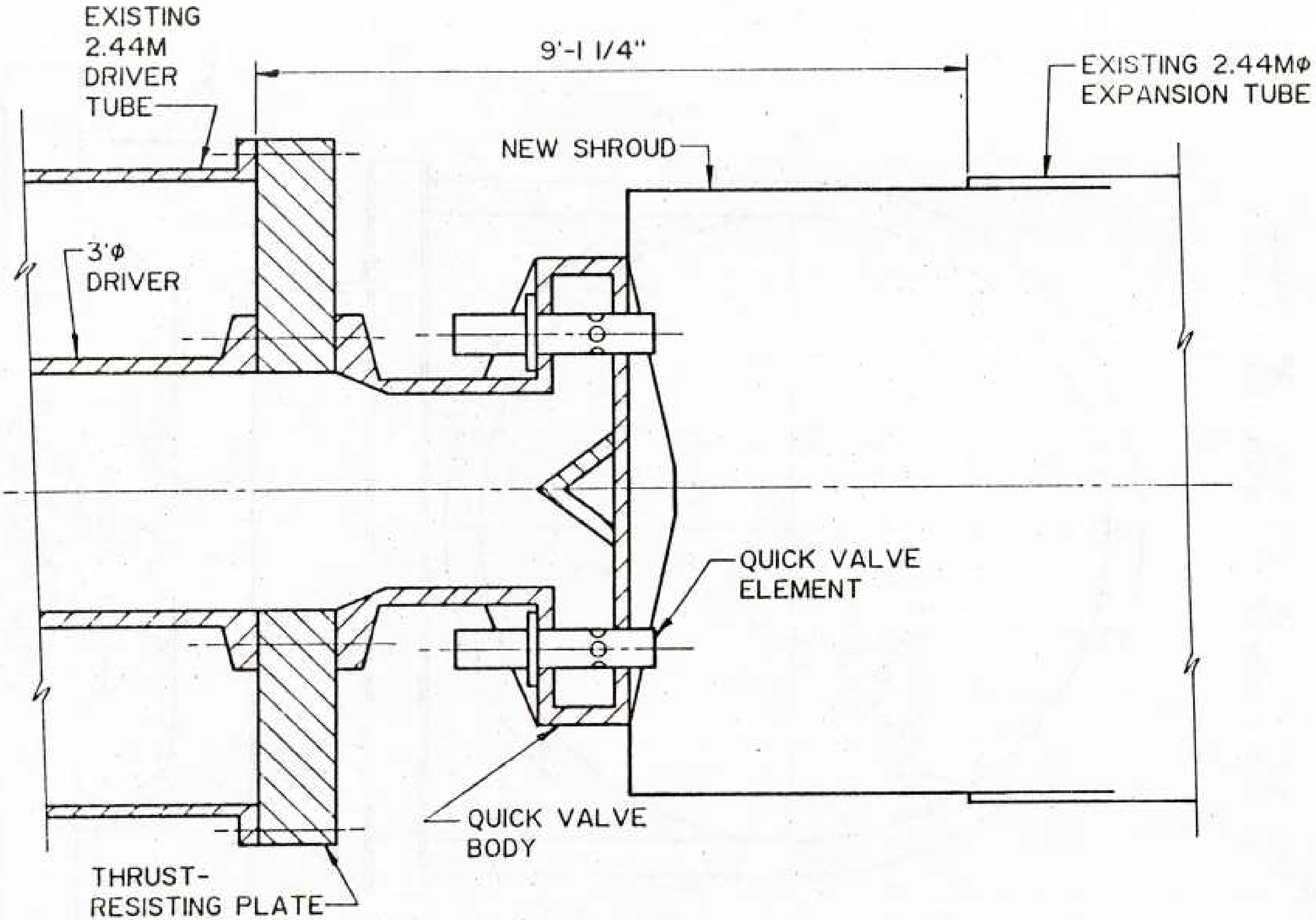
Figure 4-2

NOTE:
TRACK SUPPORT STRUCTURE IS ALSO APPLICABLE
IF THE NEW DRIVER RESTS DIRECTLY ON RAIL BED.



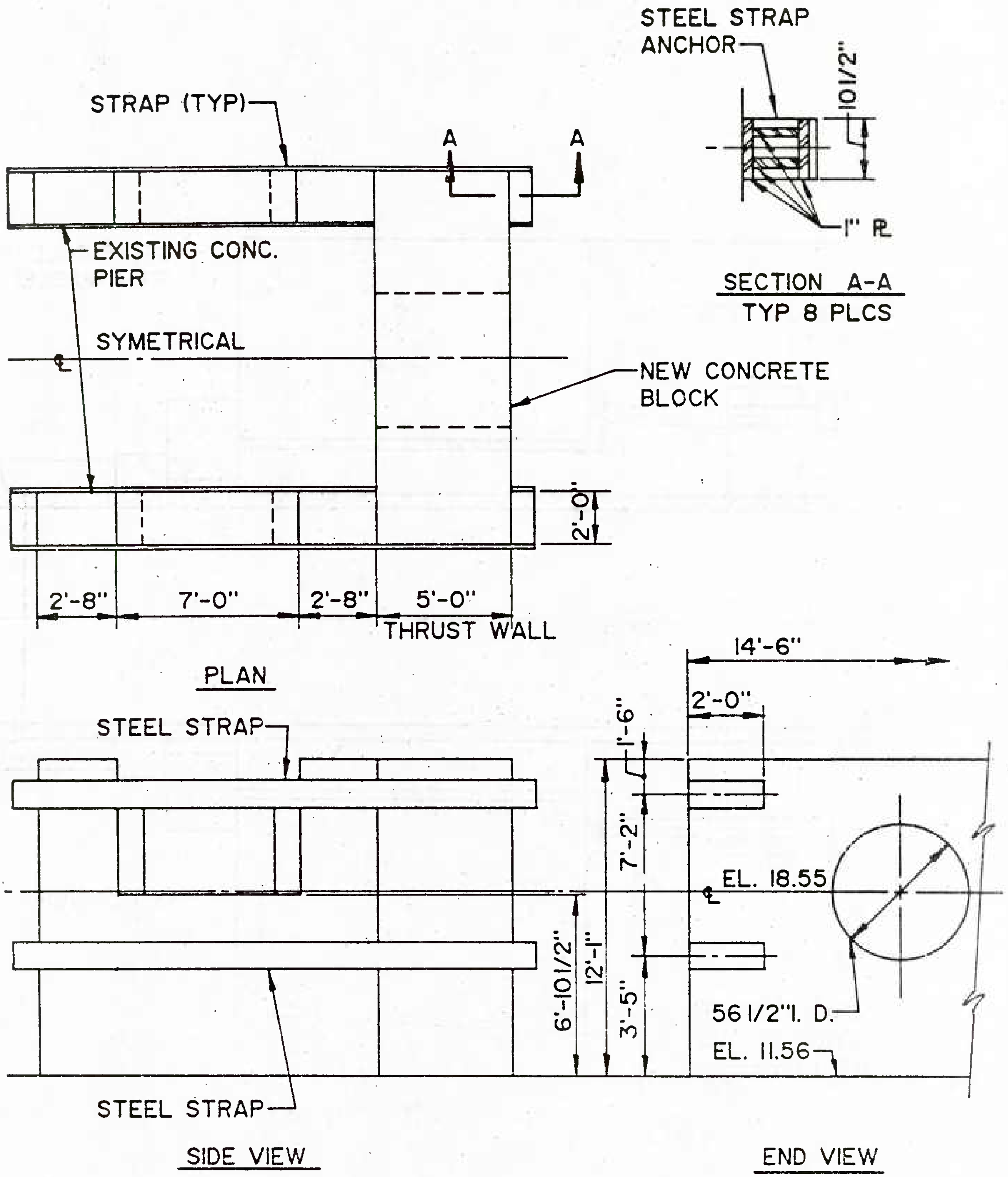
TRACK SUPPORTS

Figure 4-3



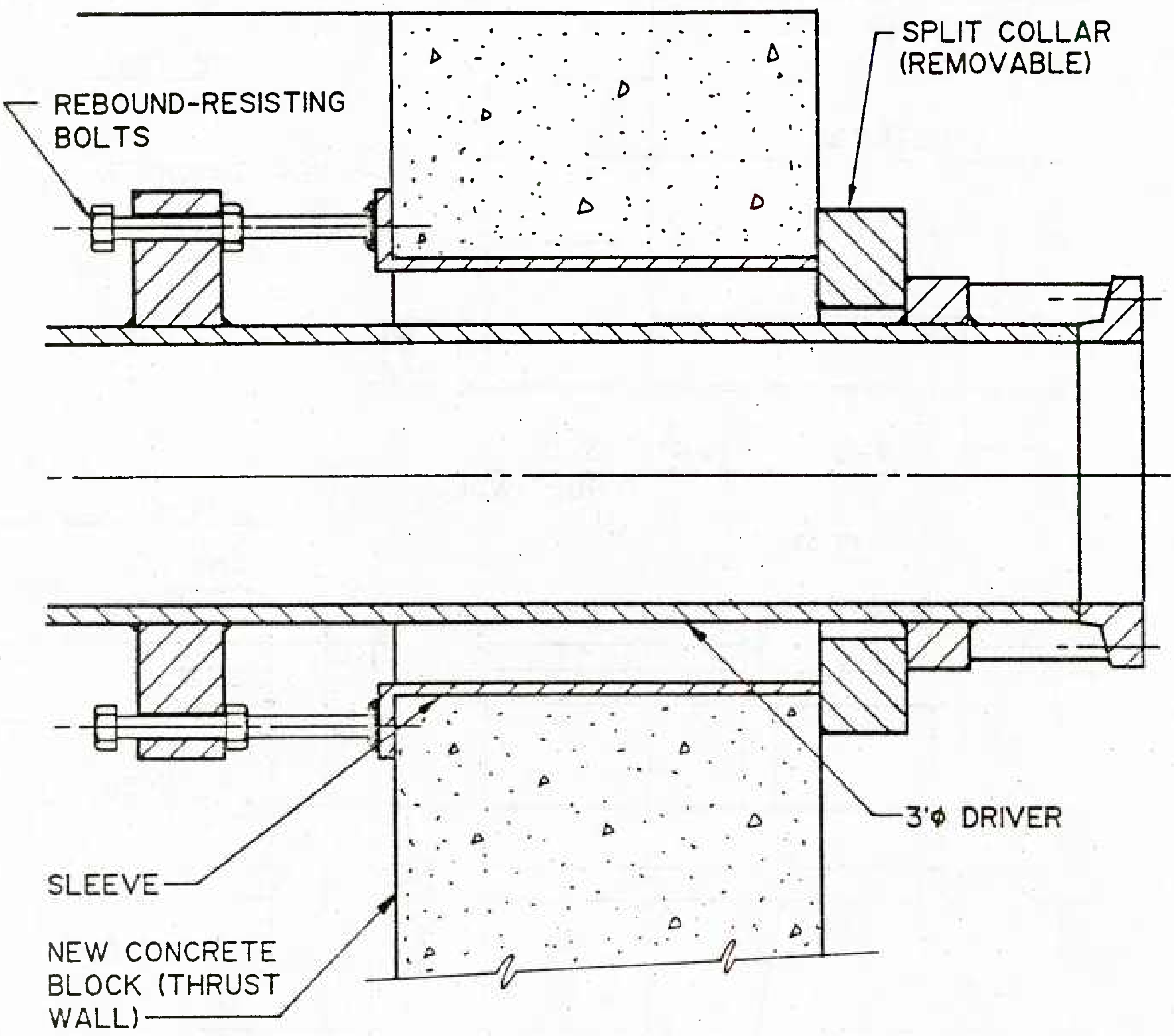
THRUST RESISTANCE SYSTEM (METHOD I) AND QUICK VALVE INSTALLATION

Figure 4-4



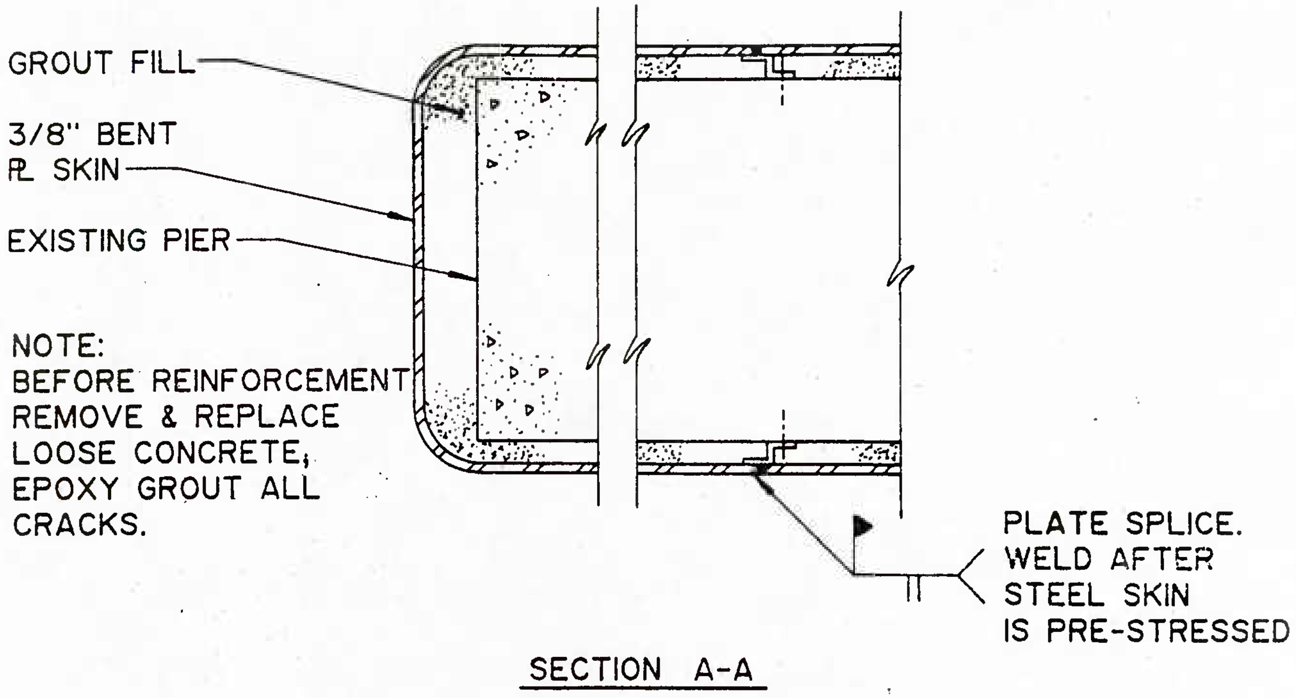
ADDITION OF CONCRETE BLOCK
TO REACTION PIER
(METHOD VI)

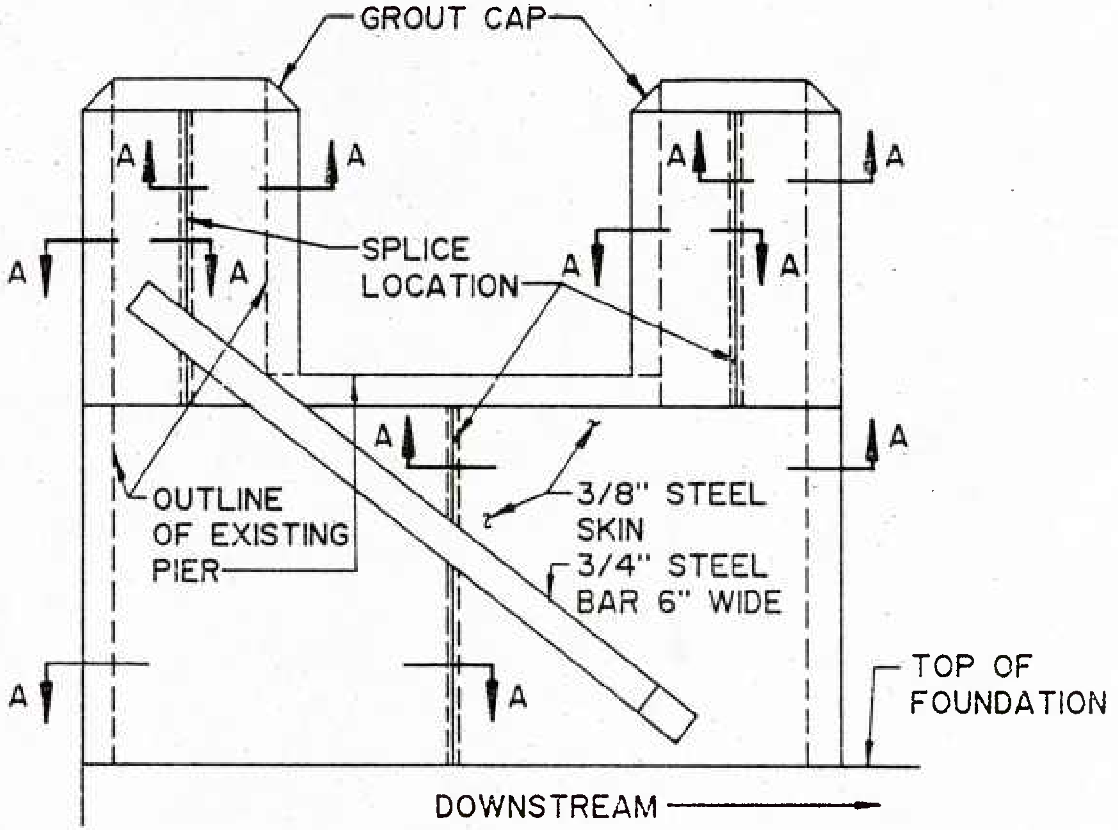
Figure 4-5



THRUST RESISTANCE SYSTEM
(METHOD VI)

Figure 4-6





REPAIR OF REACTION PIER

Figure 4-7

SECTION 5

DRIVER HEATING SYSTEM

5.1 HEATING ELEMENTS

Heating elements can be installed around the circumference of the driver tube at two-foot intervals. Twelve inches of thermal insulation would enclose the driver and its heating elements. Thirty kilowatts of electric energy will be needed to heat the driver from 0 F to 700 F in 96 hours. The 96-hour heating period was considered to be suitable for the testing program but could be decreased at the expense of greater power costs. Three tests per week and a 48-hour interval between tests were assumed. It was also assumed that the maximum temperature increase between tests would be 350 F. The steady state heat loss through tube insulation would be 20,000 btu/hour at a tube temperature of 700 F. See paragraph 5.4 for quick cooldown provision.

5.2 TEMPERATURE CONTROL

The entire tube would be maintained at a designated set temperature, and heating elements would be controlled automatically to obtain the preset temperature from a control panel in the existing control room. Temperature sensors would be located on the outer surface of the tube at four foot intervals along the length of the driver between every second heater element. Temperature control will be based upon the highest temperature reading. Heater failures would be indicated by a low temperature readout of any one sensor relative to the other readings. Separate temperature sensors can be installed through the tube wall to read gas temperature. A safety override control system would disconnect electric power from heater controllers if the temperature control failed.

5.3 MAINTENANCE OF HEATING SYSTEM

The use of electrical strip heating elements on pressure containment vessels is not a new concept. However, their application at this facility introduces the new dimension of performance under shock environment. As such, the performance of strip heaters in this environment needs to be confirmed as an objective of the Large Scale Test Bed program. Replacement of individual strip heaters may be necessary until optimum mounting and connection designs are developed. The possibility of heater replacement, even if infrequent, tends to disfavor the concept (Method I) involving enclosure of a new driver within the existing driver shell.

5.4 QUICK COOLDOWN PROVISIONS

A 12,500 cfm blower will be used to cool the driver by connecting the blower with an isolation valve at the 12 inch diameter flanged connection in the hemispherical head of the driver.

SECTION 6
CONVERGING NOZZLE AND DIAPHRAGM INSTALLATION WITH CONSIDERATION FOR A QUICK VALVE

6.1 CONVERGING NOZZLE/ORIFICE PLATE

A converging nozzle, with mating flange (1500 psi class, 36-inch inside diameter) can be attached to the driver tube flange. Figure 6-1 shows a nozzle configuration with two stages of area reduction. The first stage reduces the 36-inch diameter to 18-inches for tests requiring maximum downstream pressure. The second stage attachment can be used for obtaining a further reduction in area to achieve lower downstream pressures and longer duration waves (shown is either 12-inch or 6-inch reduction). A simple orifice plate mounted ahead the diaphragm may be used in lieu of the second and smaller stage attachments. Orifice plates have worked well in smaller scale experiments by sizing orifices to compensate for inherent losses.

6.2 QUICK VALVE

A quick valve (Figure 6-2) can be attached to the driver tube flange in place of the converging nozzle. If a quick valve can be successfully developed, it will perform the same functions as the converging nozzle and diaphragms.

6.3 DIAPHRAGM INSTALLATION

Figure 6-3 shows the proposed diaphragm installation concept. This concept allows the use of a single diaphragm, two diaphragms, or a single diaphragm and a baffle/heat shield. This device will permit testing over wide pressure and temperature ranges with diaphragms of optimum thickness. A pressure control system, as described in the following paragraph, will maintain equal pressure drop across each diaphragm when two diaphragms are installed.

6.4 PRESSURE CONTROL SYSTEM

A dual diaphragm configuration has been previously proposed to reduce LB/TS diaphragm and cutting charge costs. Such an arrangement will also limit temperature rise on downstream diaphragm. This concept would utilize two diaphragms to share the driver pressure load by limiting pressure between diaphragms to half that of gas stored in the driver.

Refer to Figure 6-4 for definition of pressures and volumes relative to the following discussion. The pressure P' of volume V' between the two diaphragms must be kept at half the driver pressure P because neither diaphragm can withstand pressure P. This can be achieved by allowing small amounts of driver gas to bleed into V' through a small manually-adjusted metering valve. The bleed-out line of V' will release gas to maintain P' at P/2 by a modulating control valve on this line. This modulating valve will be positioned by a force-balanced pneumatic operator with two unequal sized diaphragms (See Figure 6-5). A differential pressure ratio (P/P') of two can be achieved if one diaphragm area is twice that of the other. That is, the force exerted by P' on the larger area will balance for force exerted by P on the smaller area at a pressure ratio, R = P/P' = 2. A bias spring will allow slight adjustment of the pressure ratio by operating personnel.

6.4.1 Safety

For safety purposes, back-up control valves would take over in the event of failure of the main control valve. This could be achieved by providing two identical modulating valves, one of which would be connected in parallel and the other in series. If the primary operator fails in the open position, the series (downstream) valve set at a higher R ratio, would assume control. If the primary operator fails in the closed position, the parallel valve set at a lower R ratio, would take over.

6.4.2 Availability

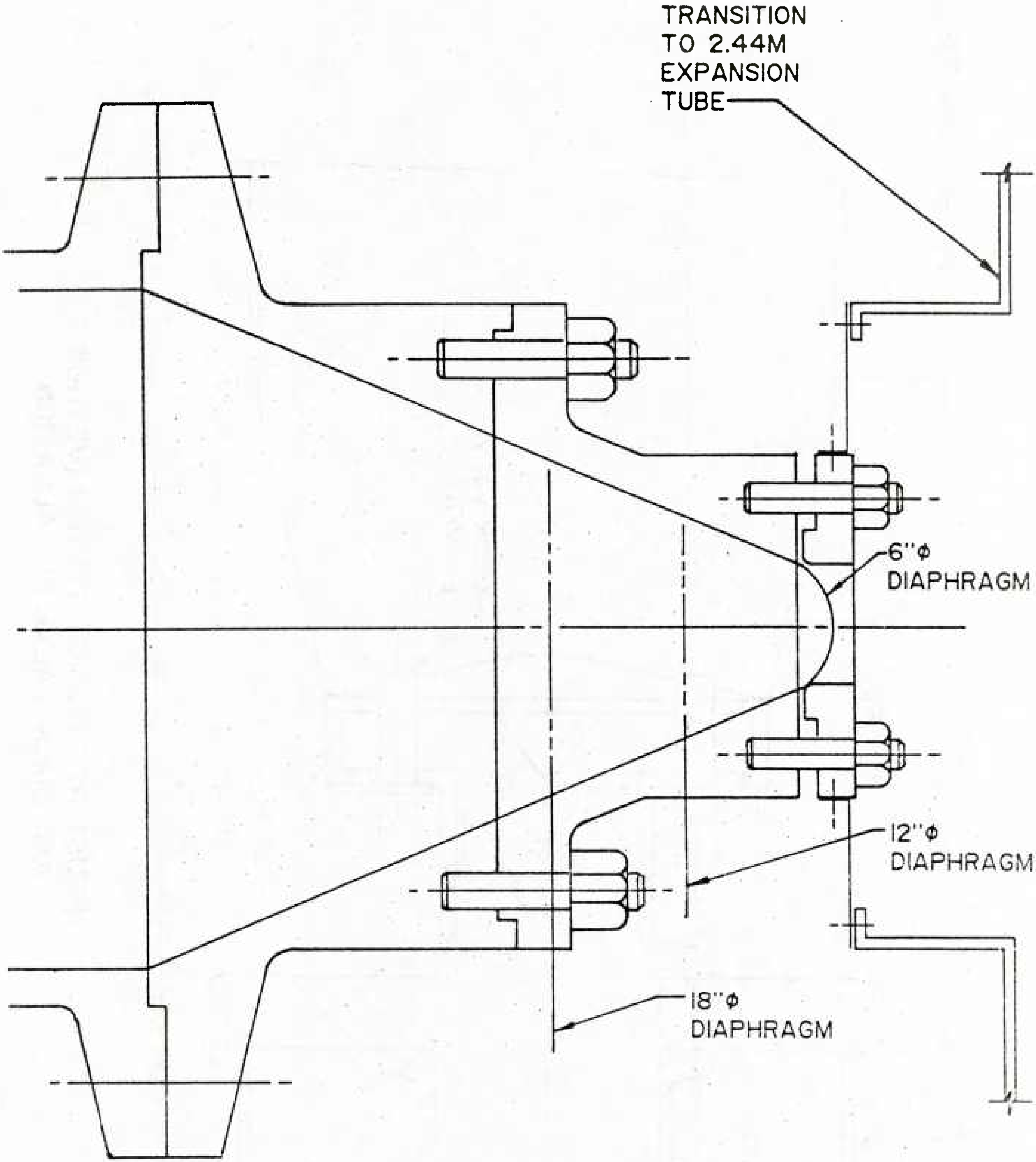
The depicted concept requires a custom-made pneumatic operator for the rated pressure of 2,000 psi. Custom fabrication may be possible by assembly of available fittings. Temperature limitations may require cooling of the bleed-out leg in radiation fins or by a water jacket supplied with the cooling system proposed in paragraph 6.4. A pressure control system composed entirely of available components is possible by using intervening pressure transducers and average relays. However, the proposed method is preferable because of its relative simplicity.

6.5 COOLING SYSTEM

A closed-cycle cooling system for the driver/diaphragm nozzle section is shown by Figure 6-6. The cooling system will have sufficient capacity to limit temperature rise of the downstream diaphragm or the quick valve to 250 F. This system will consist of:

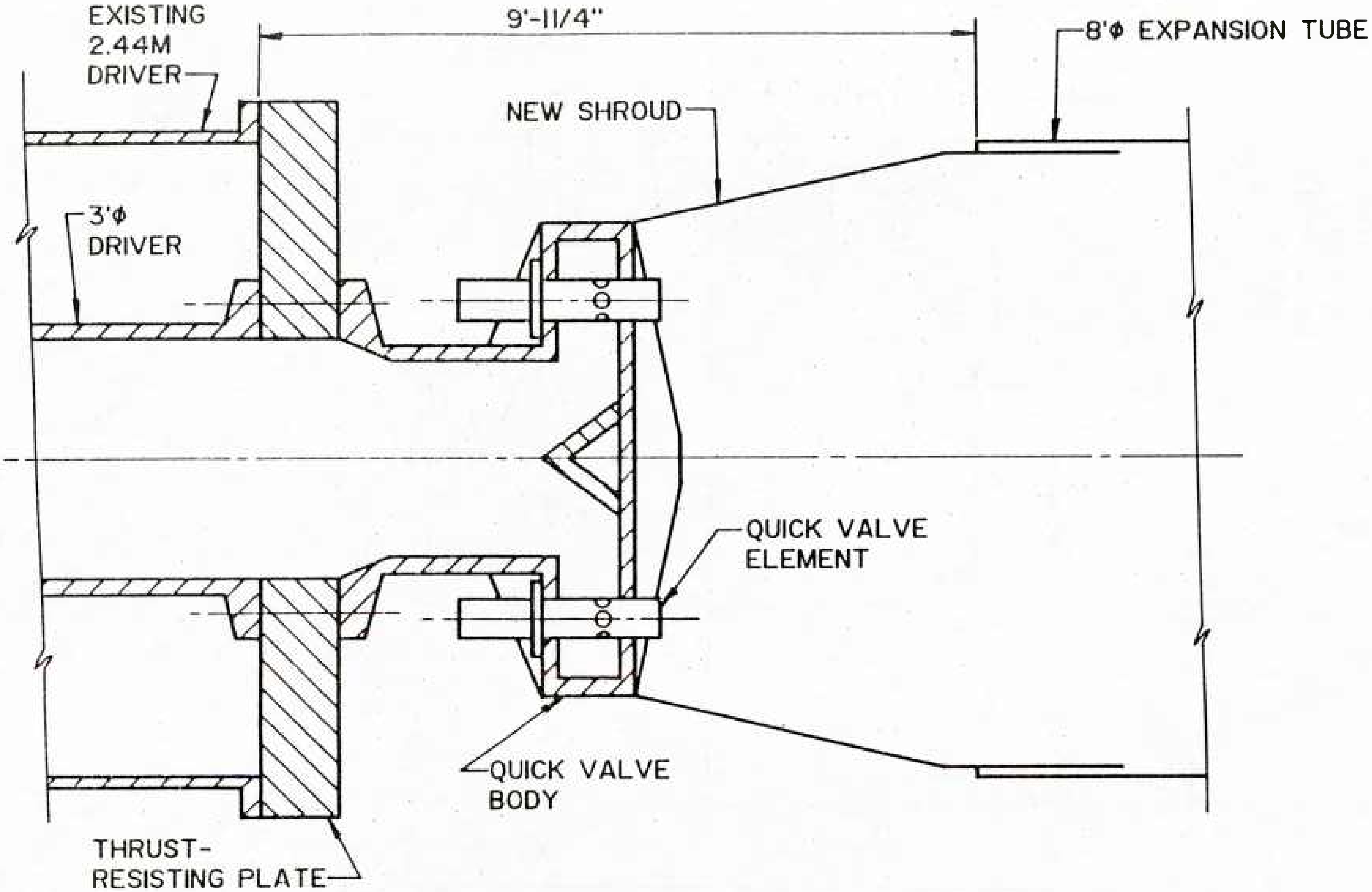
a. Cooling Jackets
b. System Pump
c. Fan Cooled Radiator
d. Expansion Tank

To prevent freeze-up, the cooling media should be an ethylene-glycol/ water mix. The cooling media would be circulated by an in-line pump through a fan-cooled radiator where it would be cooled to within a few degrees of the ambient air temperature. An expansion tank would be provided to equalize flow conditions within the system and to allow a reservoir of liquid to compensate for leaks and spillage. Water jackets would envelope surfaces to be cooled at the diaphragm section (See Figure 6-7), and these jackets would be piped in a counterflow configuration.



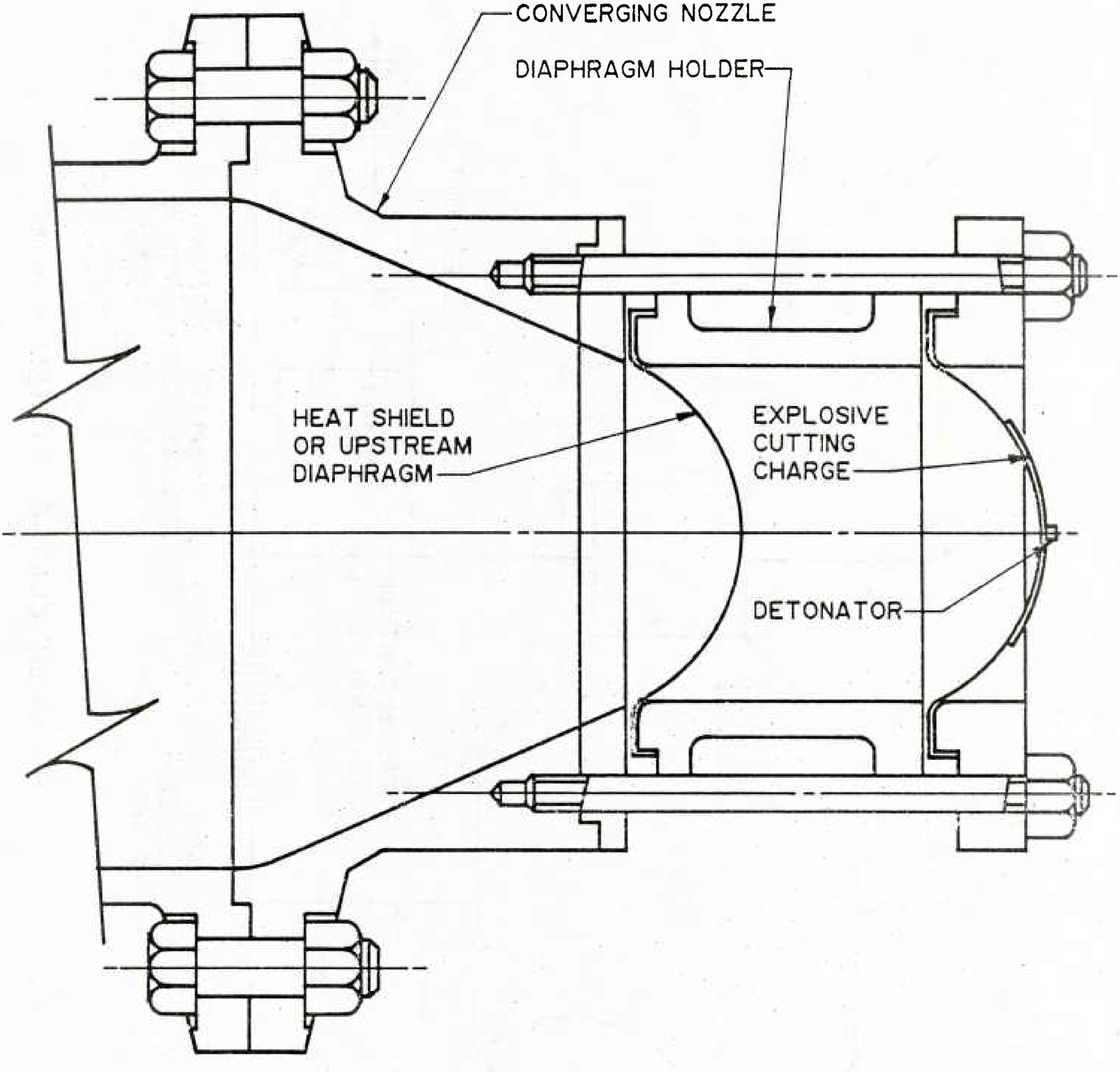
METHOD OF INSTALLING SMALLER CONVERGING NOZZLES AND DIAPHRAGMS

Figure 6-1



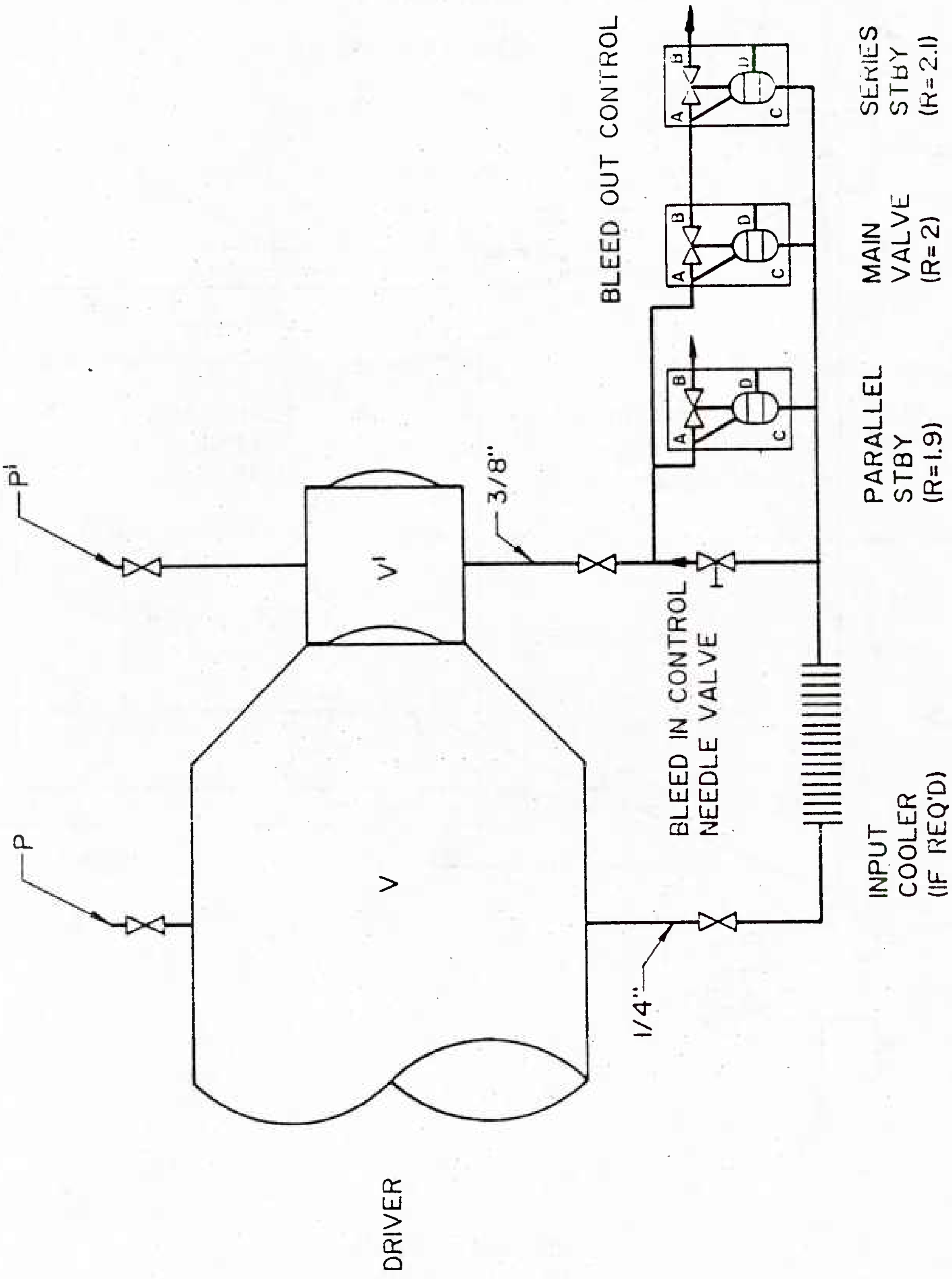
THRUST RESISTANCE SYSTEM (METHOD I)
AND QUICK VALVE INSTALLATION

Figure 6-2



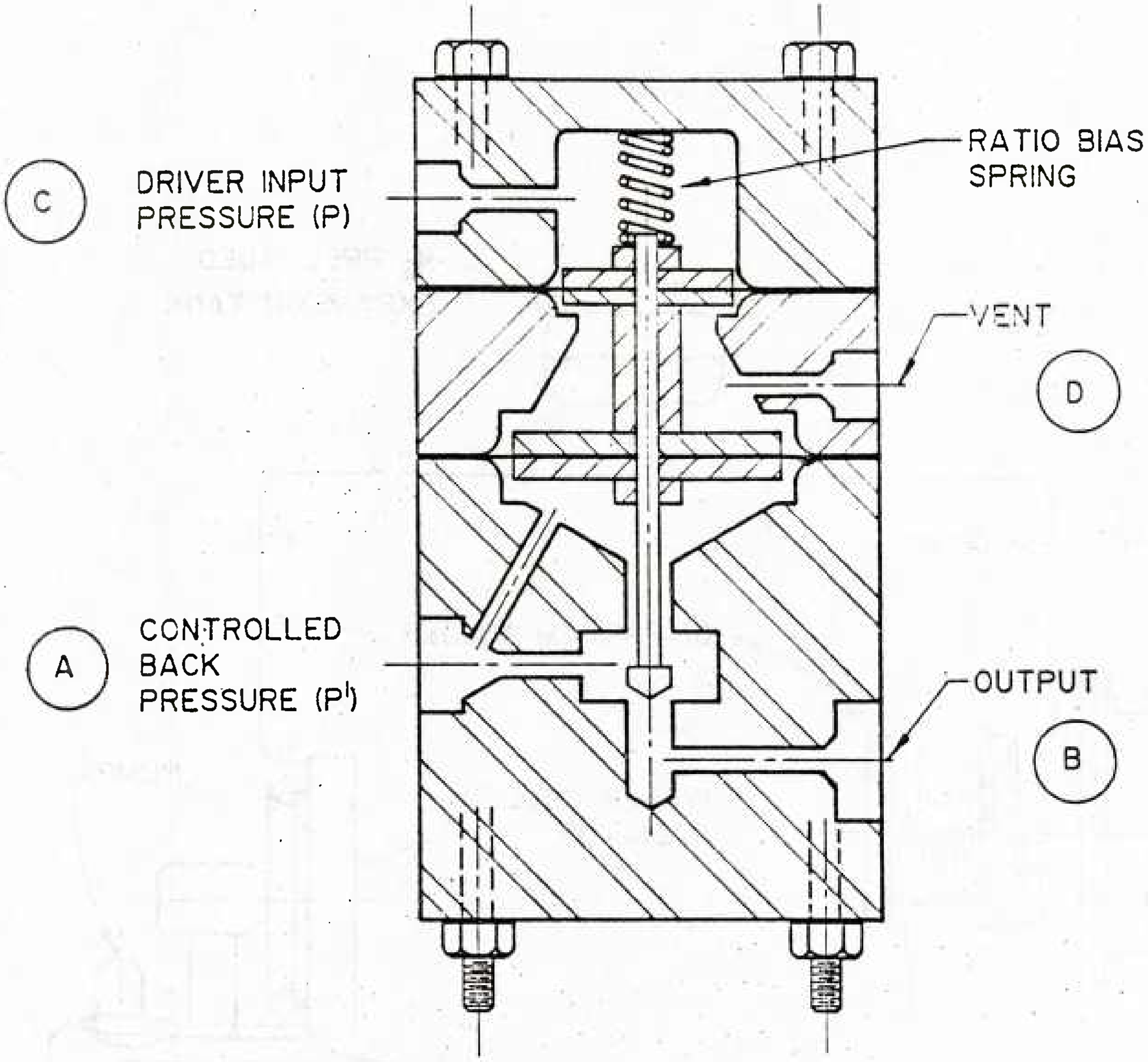
DUAL DIAPHRAGM INSTALLATION

Figure 6-3



PRESSURE CONTROL SYSTEM SCHEMATIC

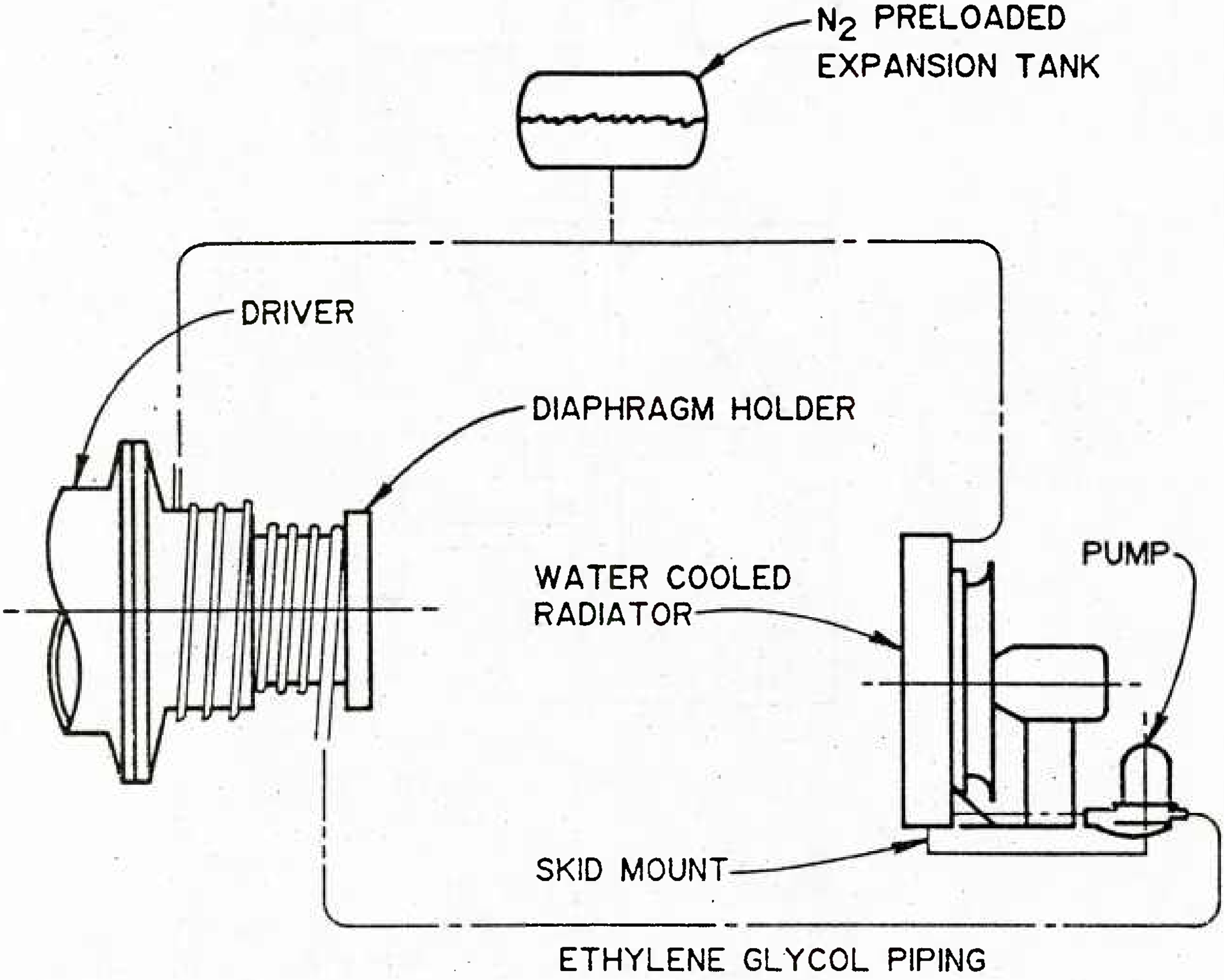
Figure 6-4



PRINCIPLE OF OPERATION:
SINCE FORCE EQUALS PRESSURE TIMES AREA, LESS BACK PRESSURE IS REQUIRED TO BALANCE A GIVEN INPUT. IN THE 2:1 RATIO MODEL, AN INPUT OF 1800PSI WOULD RESULT IN A 900PSI BACK PRESSURE.

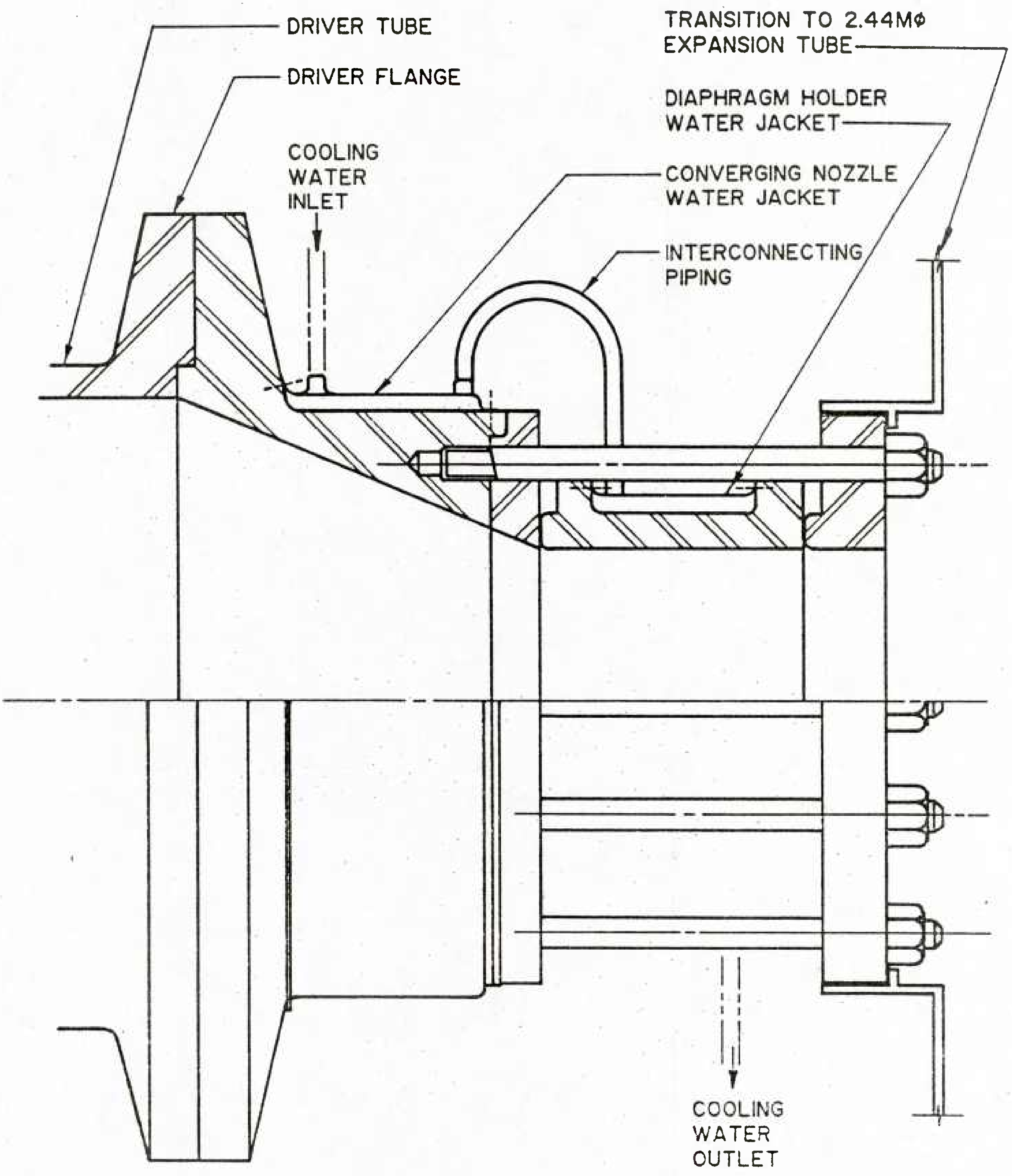
FORCE BALANCED
PNEUMATIC OPERATOR

Figure 6-5



CLOSED CYCLE NOZZLE/VALVE
COOLING CIRCUIT

Figure 6-6



CONVERGING NOZZLE
AND DIAPHRAGM HOLDER
WITH WATER COOLING

Figure 6-7

SECTION 7
HIGH PRESSURE GAS SUPPLY

7.1 SYSTEM DESCRIPTION

The proposed high pressure gas system will utilize liquid nitrogen from an on-site storage tank, positive displacement pumps to pressurize the driver, and two vaporizers to gasify the liquid nitrogen. Liquid nitrogen will be vaporized by heat absorbed from air with two vaporizers and brought to within 5 C of ambient temperature with two booster heaters. Two pumps will be provided to pressurize the driver tube to its maximum level in a one-hour period after a 10-minute gravity cool down of the pump suction lines. If one pump fails, the other pump would pressurize the driver tube in twice the time needed for a two pump operation. The pumps, their lubrication and control systems, switchgear, and trim heaters should be located in a 12-foot by 20-foot enclosure for weather protection. A schematic diagram of the liquid nitrogen system is shown on Figure 7-1.

7.2 PUMPS

The required pump capacity was estimated to be 5 gpm at 2,000 psi. Pumps should be monitored for cool down, loss of suction, recirculation, and cavitation by a microprocessor which also logs pump running time. If the storage tank is pressurized during flow conditions, booster pumps will not be needed in the suction line to the main pumps. Several spare "cold heads" should be kept on hand because this part of a positive displacement pump is a high maintenance item.

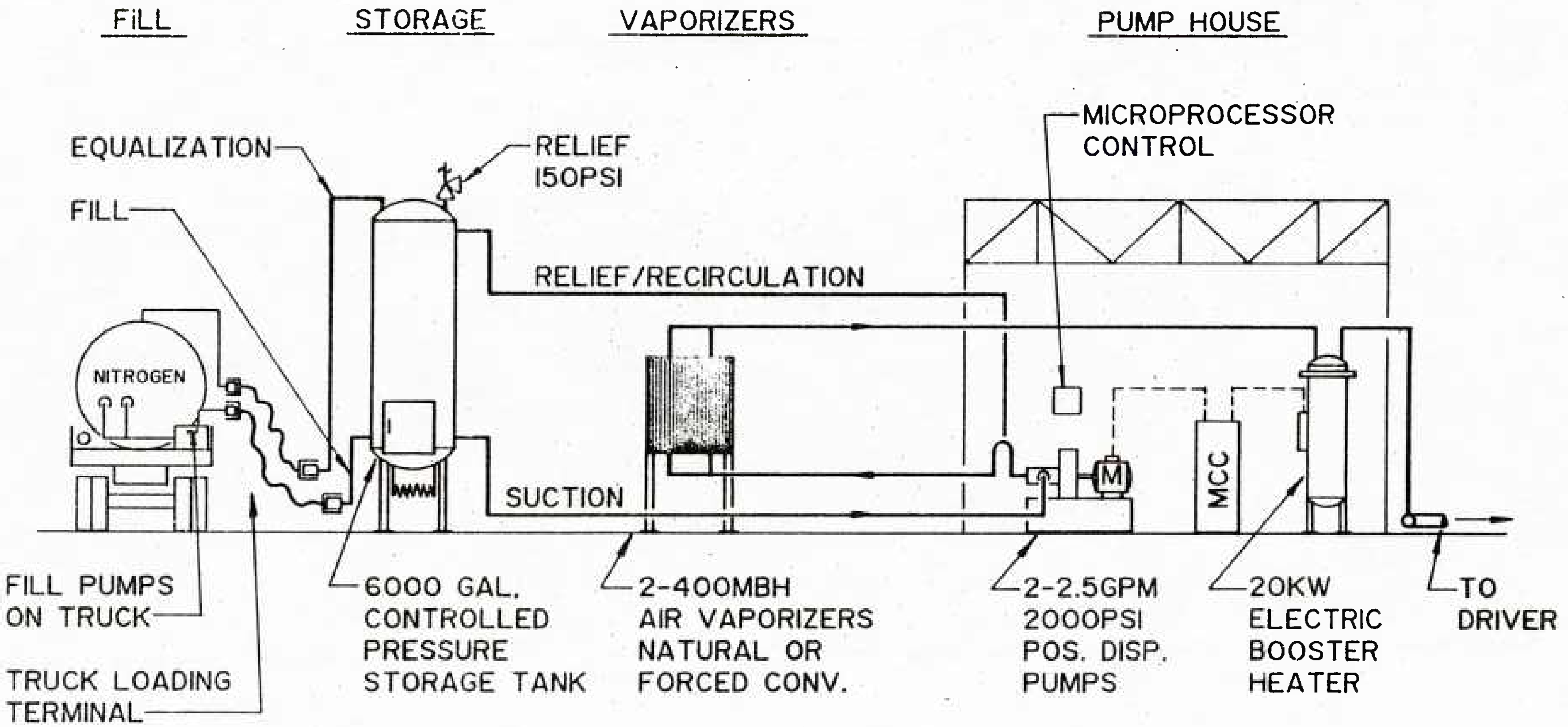
7.3 STORAGE TANK AND FILL STATION

The required storage tank capacity was estimated to be 6,000 gallons to cover any conceivable weekly consumption. Boil-off losses are expected to not exceed one percent of the tank content per day. A fill station is needed at the storage tank to accomodate quick connect and disconnect of flexible hoses on LN2 supply trucks. Filling is normally done using pumps on supply trucks. Rental of a complete storage tank and control system from a liquid nitrogen supplier is often cost-effective for "hospital size" installations such as the proposed system. For this reason, purchase cost of the storage tank was not included in estimates for this study.

7.4 VAPORIZERS AND BOOSTER HEATERS

The two vaporizers will be batteries of externally finned tubes that are connected in parallel. Heat needed for vaporization will be supplied by ambient air that circulates around the fins by natural convection. Liquid nitrogen will enter the bottom headers of vaporizers under pump pressure to be forced through the finned tubes. After complete vaporization in the tubes, the pressurized gas will be collected in headers at the top of vaporizers. The temperature of nitrogen gas leaving the headers will depend upon the ambient temperature and upon the amount of ice build-up on the fins. The rate of heat exchange between ambient air and the nitrogen will be influenced by the built-up ice.

Electric indirect (isopentane bath) trim heaters will be required to boost the temperature of gas entering the driver in the winter and to more closely control the discharge temperature of the vaporizers. A combination of air vaporizers and trim heaters is normally more economical than forced convection air vaporizers equipped with electric defrost.



LIQUID NITROGEN SYSTEM
SCHEMATIC DIAGRAM

Figure 7-1

SECTION 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 GENERAL

The 2.44-meter shock tube at BRL can be modified to serve as a Large Scale Test Bed for LB/TS research. Although significant costs are involved, modification of the existing facility has several advantages over an entirely new facility. These advantages are:

a. The existing reaction foundation, a major element of the facility, can be reused "as is".

b. The existing expansion section can be reused with only minor alterations.

c. Personnel protection is available in the existing Control Building. Diaphragm rupture can be controlled from existing equipment in this building. Controls for nitrogen pressurization, tube heating, tube ventilation, and nozzle cooling can be added within this building.

d. The existing Diaphragm Change Building can be used for shop operations during Test Bed experiments.

e. Existing electrical power is adequate for heating and charging the new driver.

f. No additional real estate is required.

g. Compliance with environmental regulations will be simplified.

h. The existing facility is located in relative proximity to administrative support offices.

8.2 CONSTRUCTION COSTS

The ultimate disposition of the BRL Shock Tube Facility is unknown. Consequently, an optimum concept for its temporary conversion to LB/TS Test Bed usage cannot be determined with certainty. Costs of two methods (I and VI) for its modification were derived so the value of keeping the existing tube intact could be assessed. These costs are summarized in Table 8-1; the total procurement/construction was estimated to be about $1.1 million. Method VI will cost about $32,000 less than Method I.

TABLE 8-1
COST ESTIMATE FOR INSTALLING HIGH PRESSURE DRIVER

MAJOR COST ELEMENT NEW DRIVER INSTALLATION	METHOD I	METHOD VI
TUBE & FLANGE	$ 94,600	$ 94,600
HEATING SYSTEM	50,000	50,000
INSULATION SYSTEM	37,000	37,000
TUBE COOLING SYSTEM	10,200	10,200
VALVE/DIAPHRAGM COOLING	10,000	10,000
ANCHOR SYSTEM	37,800	49,500
3 FT TUBE SUPPORTS	21,000	19,600
3 FT GROUND SUPPORT	---	5,250
8 FT GROUND SUPPORT	5,250	---
REACTION BLOCK REPAIR	18,320	18,320
3 FT TUBE INSTALLATION	110,000	48,000
WEATHER COVER	---	24,300
SUBTOTAL	$394,170	$366,770
15% CONTINGENCY	59,126	55,016
TOTAL	$453,926	$421,786
NITROGEN SYSTEM	$106,000	$106,000
15% CONTINGENCY	15,900	15,900
TOTAL	$121,900	$121,900
QUICK VALVE DEVELOPMENT	$ 50,000	$ 50,000
QUICK VALVE COST	$380,000	$380,000
QUICK VALVE COMPUTER AND INTERFACE	15,000	15,000
VALVE SUPPORT	3,000	3,000
TRANSITION TO 8 FT	8,000	8,000
SUBTOTAL	$456,000	$456,000
15% CONTINGENCY	68,400	68,400
TOTAL	$524,400	$524,400
DIAPHRAGM MOUNT AND NOZZLE	24,400	24,400
TRANSITION TO 8 FT	8,000	8,000
SUBTOTAL	$ 32,400	$ 32,400
15% CONTINGENCY	4,860	4,860
TOTAL	$ 37,260	$ 37,260

Detailed cost breakdowns are included as Appendix C.

8.3 CONSTRUCTION SCHEDULE

Figures 8-1 and 8-2 show construction schedules for Method I and Method VI, respectively. They indicate a conventional construction period of about ten months, regardless of the method pursued. Through closely controlled construction management, these schedules may be foreshortened to about eight months.

Engineering design, construction advertisement, or contractual procedures are not included in construction schedules.

8.4 RECOMMENDATIONS

a. The BRL 2.44-meter shock tube should be modified as outlined in previous sections for Method VI and as shown on Figure 8-3. Accessibility of heating elements and lower initial costs are the primary advantages of this method. Method I can be used in lieu of Method 6 if construction expediency evolves as the primary selection factor.

b. A plan should be developed for thorough measurement of stress levels in the new driver.

c. The procurement/construction program should include allowances for contingencies which develop from early test results, i.e.:

(1) The quick valve does (or does not) shape waves by sequential closing of its ports.

(2) The quick valve does (or does not) permit formation of a steep shock front when it opens.

Purchase of the double-diaphragm section and diaphragms could be postponed or avoided entirely, depending upon results of quick valve testing.

METHOD I - CONSTRUCTION SCHEDULE

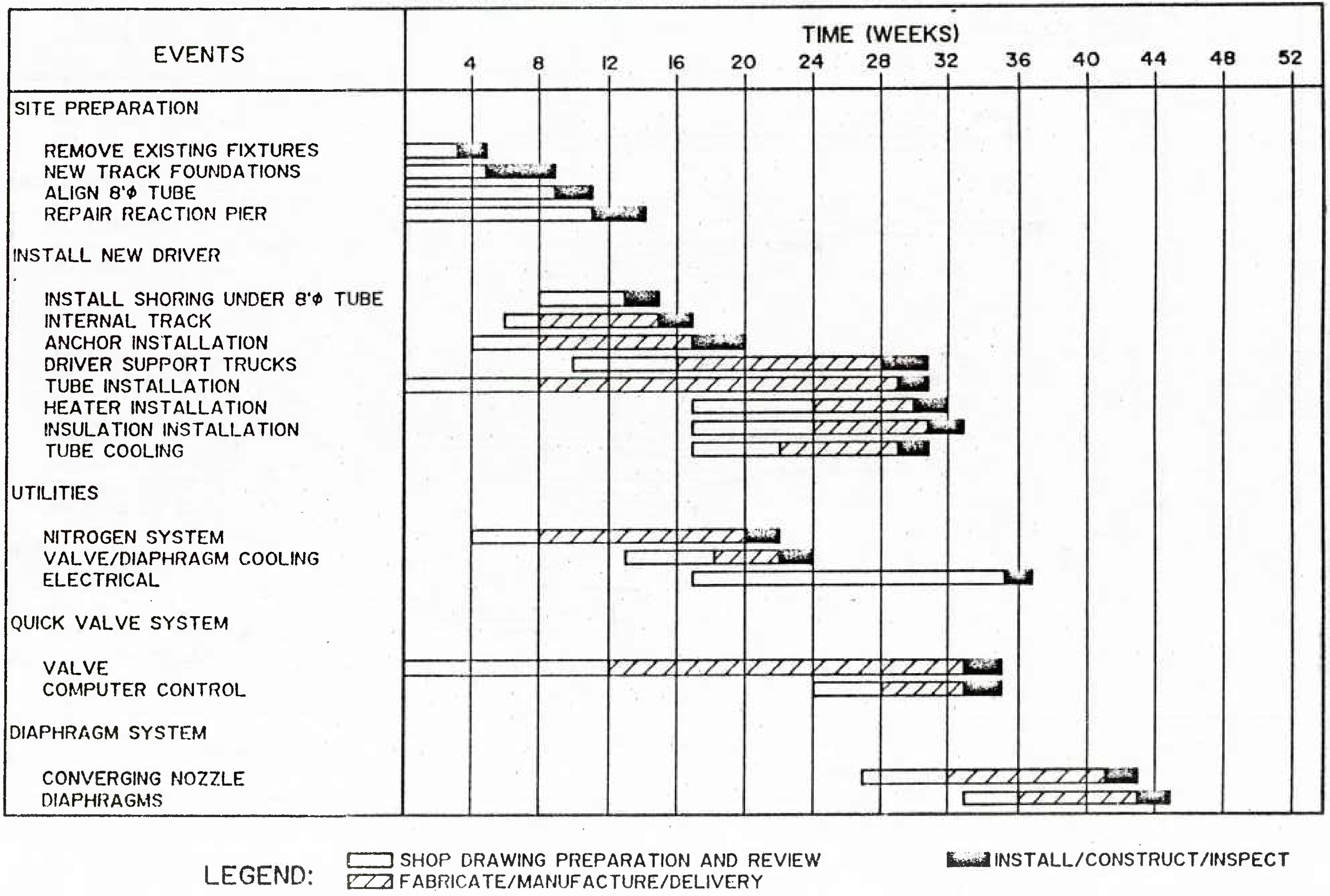


Figure 8-1

METHOD VI - CONSTRUCTION SCHEDULE

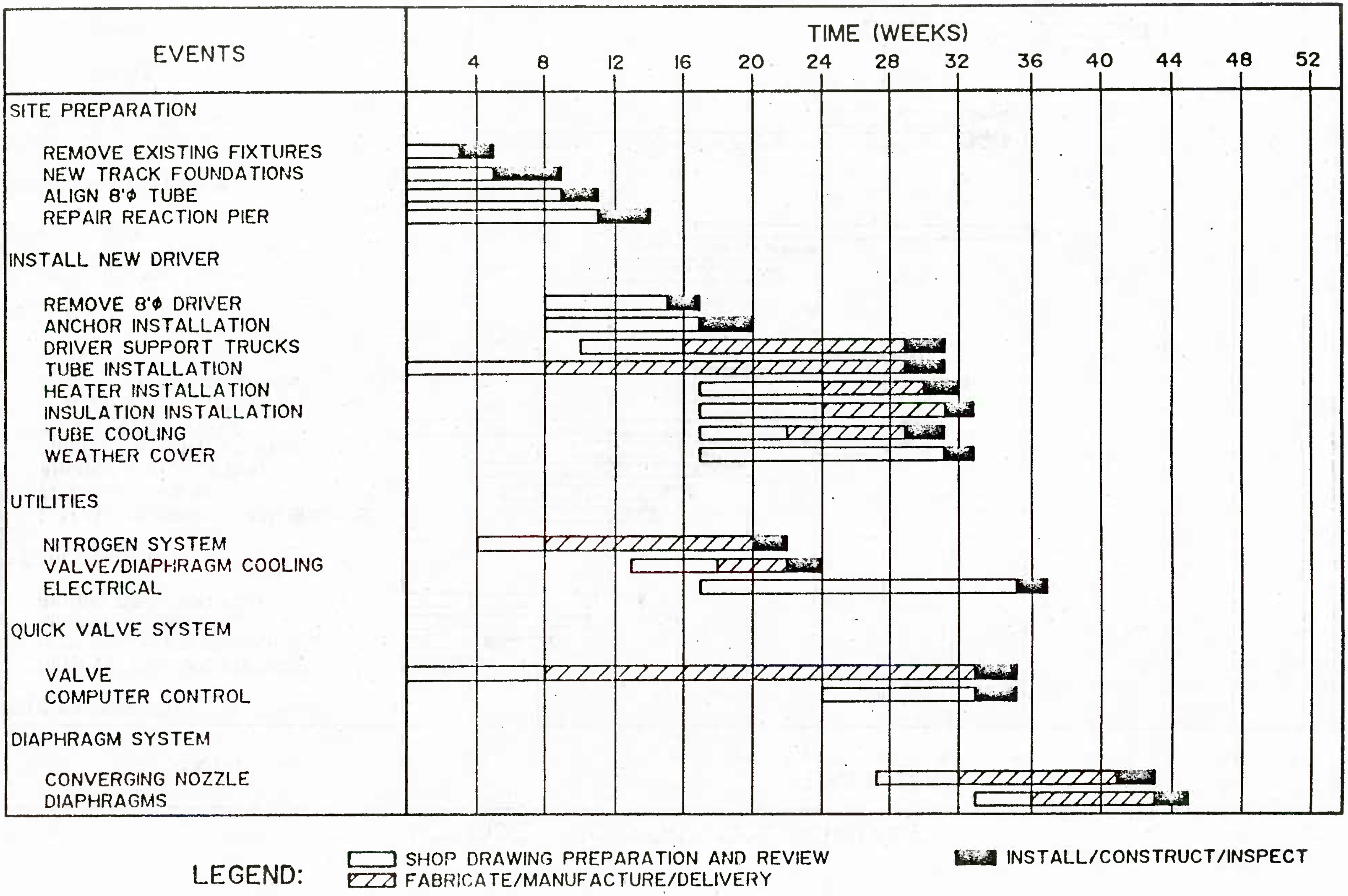
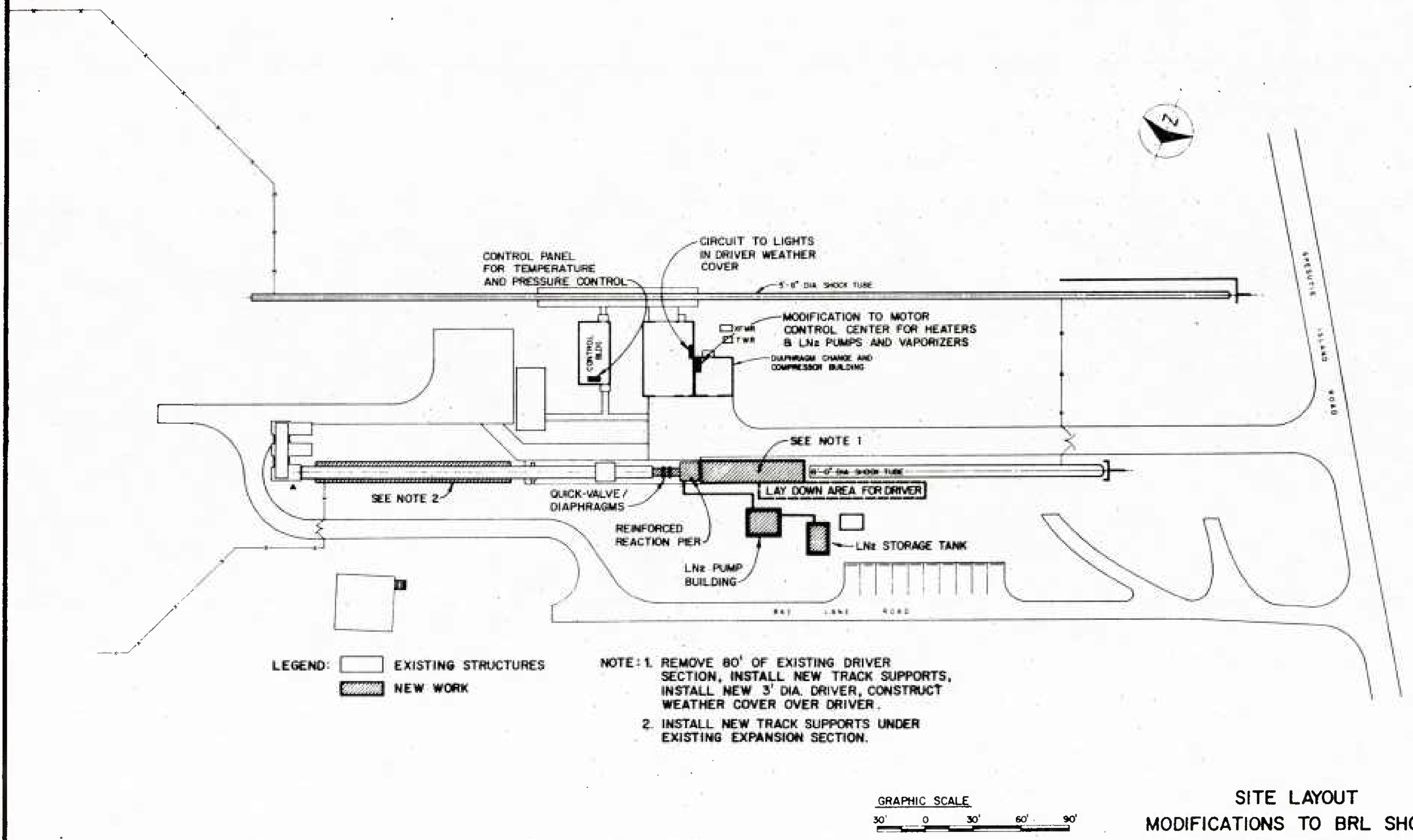


Figure 8-2



SITE LAYOUT
MODIFICATIONS TO BRL SHOCK
TUBE FACILITY

Figure 8-3

APPENDIX A

LIST OF REFERENCES

1. Black & Veatch, Engineers-Architects, System Integration Design Study for a Large Blast/Thermal Simulator (Draft), Defense Nuclear Agency, Washington, DC, 23 November 1986.

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3. M. J. Zucrow, J. D. Hoffman, Gas Dynamics, Vol. I, John Wiley & Sons, New York, NY, 1976.

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APPENDIX B

COMPUTATION OF LONGITUDINAL DYNAMIC EFFECTS

PURPOSE: Fast Fourier Transform of Logitudinal Stress Test Results

$j := 0 .. 63$

$x_j :=$
4.5
5
6.8
6.9
7
8.5
9.5
9.4
9
8.2
7.5
6.5
5.5
4.7
5.2
5.8
6.5
6.5
5.5
4.9

$x_{j+20} :=$
3.5
2.9
1.7
1.8
2.5
4.
3.7
2.9
1.6
1
0
-.4
-.8
-.8
-.7
-.8
-1.1
-2.2
-3
-3.1
-3.3
-4
-4.3
-4
-2.8
-2
-2.6
-3.2
-3.5
-3.4

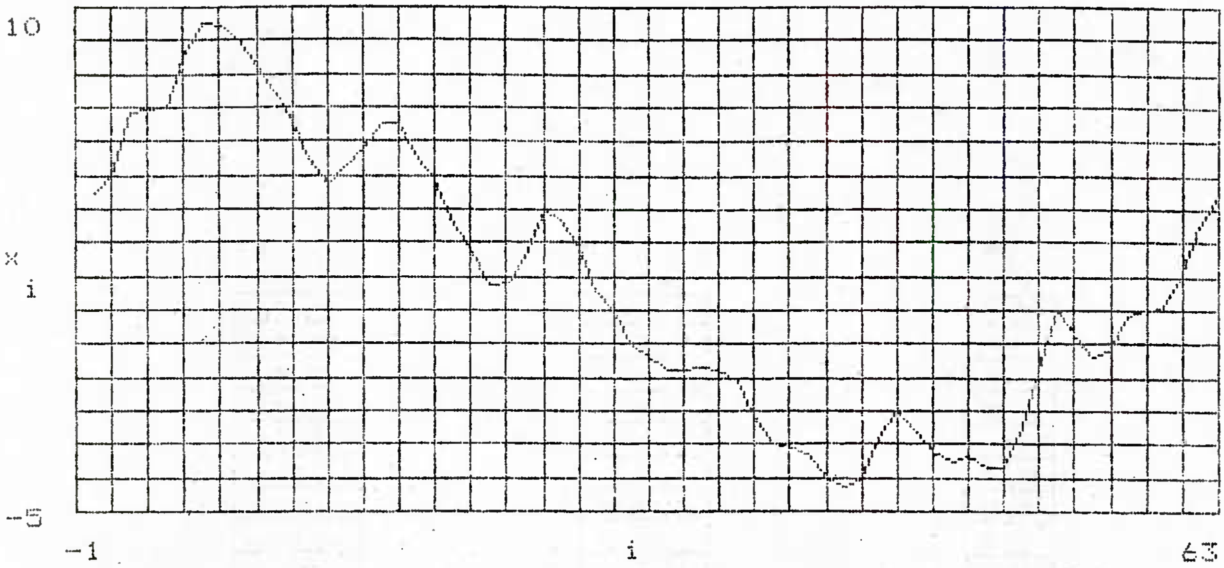
$x_{j+50} :=$
-3.7
-3.7
-2.5
-.8
1
.2
-.4
-.1
.8
1
1.1
2.1
3.5
4.5

$c := \mathrm{fft}(x)$

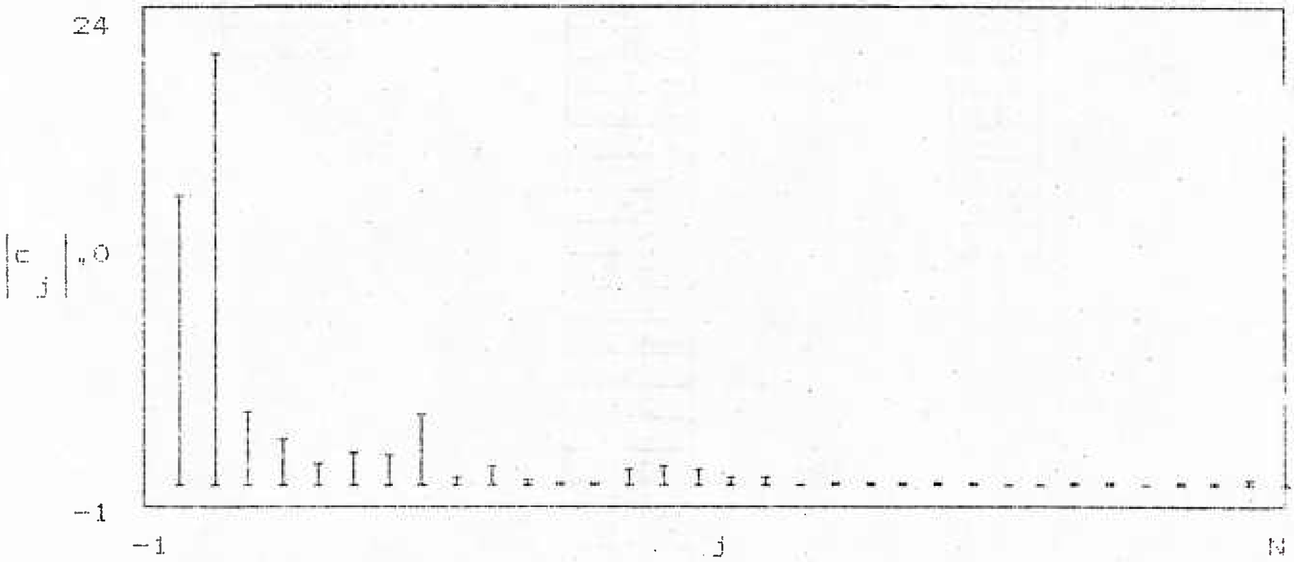
$N := \mathrm{last}(c) \quad N = 32$

$j := 0 .. N$

$i := 0 \,..63$



Graph of Input Data



Coefficients c

Table of Results

c_j
14.5
10.891 + 18.596i
2.721 + 2.492i
-0.632 + 2.339i
-0.752 + 0.922i
-1.257 + 1.174i
-1.509 + 0.37i
2.844 - 2.306i
0.496 + 0.029i
-0.959 - 0.347i
0.078 + 0.334i
0.025 + 0.173i
0.2 + 0.029i
0.742 + 0.47i
-0.537 - 0.866i
-0.778 - 0.417i
-0.512 + 0.112i
-0.425 - 0.205i
-0.111 - 0.003i
-0.174 - 0.132i
0.037 - 0.179i
0.018 - 0.274i
-0.088 - 0.246i
0.117 - 0.095i
0.054 - 0.046i
0.021 + 0.069i
0.138 - 0.142i
0.148 - 0.136i
-0.035 - 0.037i
-0.217 + 0.127i
0.009 - 0.177i
0.237 + 0.183i
-0.075

$\mathrm{delta\_t} := .0004878 \qquad i := 0 \,..\, 31$

$$\mathrm{frequency}_i := \frac{i}{64 \cdot \mathrm{delta\_t}} \qquad \mathrm{phase}_i := \mathrm{angle}\left[\mathrm{Re}\left[c_i\right], \mathrm{Im}\left[c_i\right]\right]$$

$$\mathrm{delay}_i := \frac{\mathrm{phase}_i}{2 \cdot c} \cdot \mathrm{delta\_t} \cdot N$$

Frequency (Hz) $\mathrm{frequency}_i$	Maginitude of coefficient $\lvert c_i \rvert$	Phase Shift (radians) phase_i	Delay (sec) delay_i
0	14.5	0	0
32.032	21.551	1.041	0.003
64.063	3.69	0.742	0.002
96.095	2.423	1.835	0.005
128.126	1.19	2.255	0.006
160.158	1.72	2.39	0.006
192.189	1.554	2.901	0.007
224.221	3.662	5.602	0.014
256.253	0.497	0.058	$1.434 \cdot 10^{-4}$
288.284	1.02	3.489	0.009
320.316	0.343	1.342	0.003
352.347	0.175	1.427	0.004
384.379	0.202	0.144	$3.589 \cdot 10^{-4}$
416.41	0.878	0.565	0.001
448.442	1.019	4.158	0.01
480.474	0.883	3.634	0.009
512.505	0.525	2.926	0.007
544.537	0.472	3.591	0.009
576.568	0.111	3.166	0.008
608.6	0.218	3.791	0.009
640.631	0.183	4.918	0.012
672.663	0.275	4.778	0.012
704.695	0.261	4.367	0.011
736.726	0.151	5.6	0.014
768.758	0.071	5.574	0.014
800.789	0.072	1.279	0.003
832.821	0.198	5.482	0.014
864.852	0.201	5.541	0.014
896.884	0.051	3.946	0.01
928.916	0.251	2.614	0.006
960.947	0.177	4.763	0.012
992.979	0.3	0.656	0.002

Now, evaluate the effect of the most prominent coefficients by setting others equal to zero. The prominent ones are 0,1, and 7.

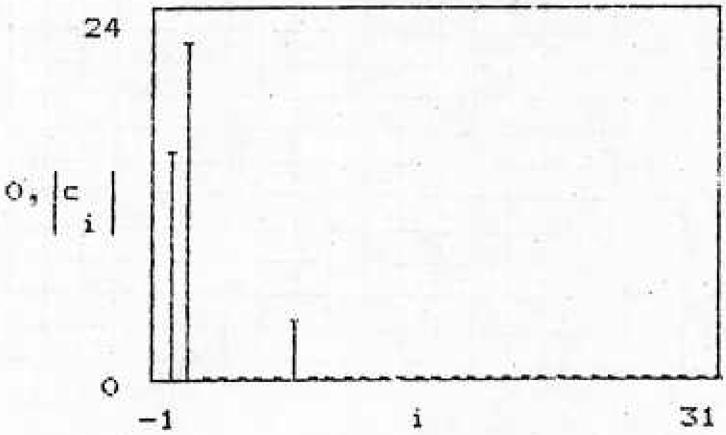
$i := 2 .. 6$

$$c_i := \begin{array}{|c|}\hline 0\\\hline 0\\\hline 0\\\hline 0\\\hline 0\\\hline 0\\\hline\end{array}$$

$i := 8 .. 31$

$$c_i := \begin{array}{|c|}\hline 0\\\hline\end{array}$$

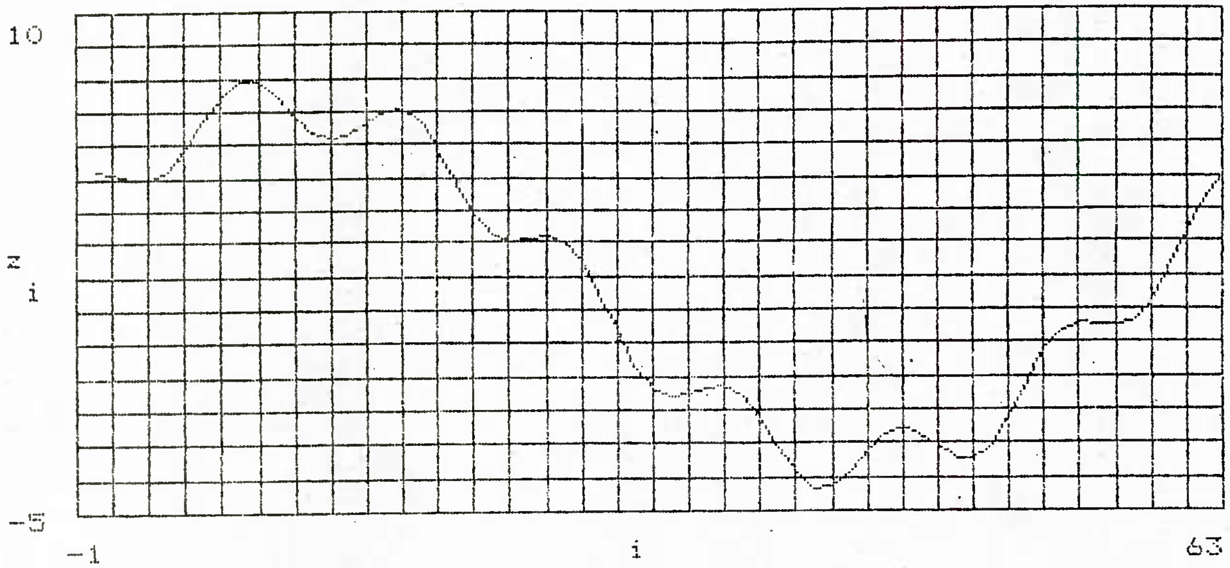
$i := 0 .. 31$

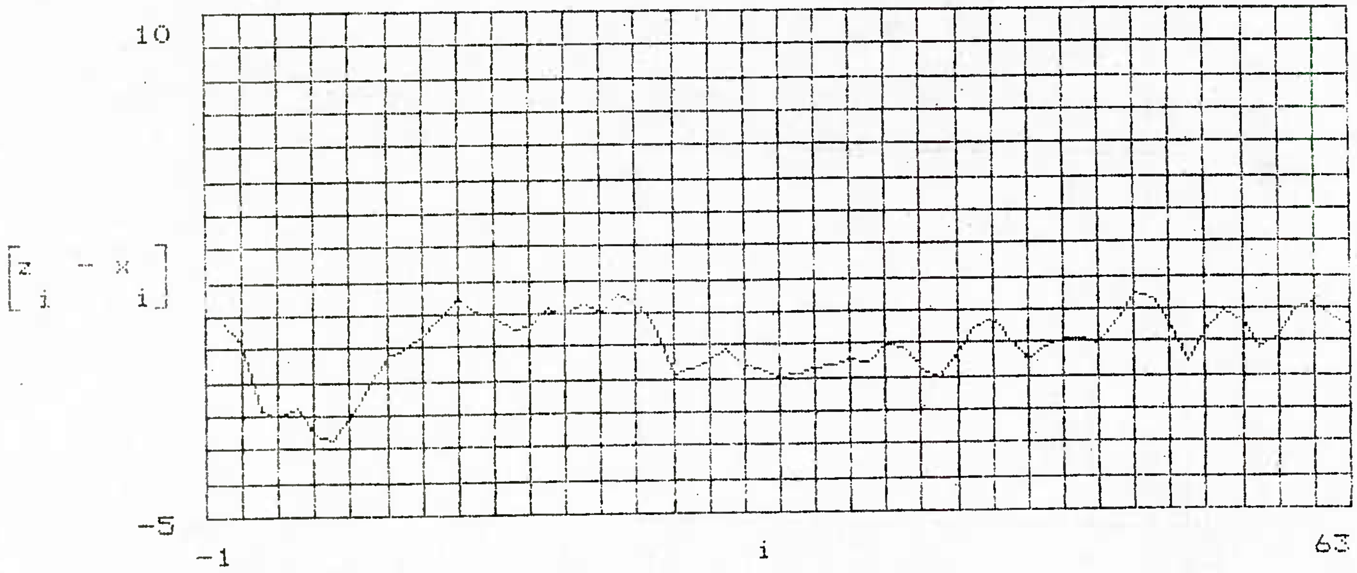


Now take inverse FFT to regenerate curve

$z := \mathrm{ifft}(c)$

$i := 0 \,..\, 63$


Graph of Reconstructed Data


Error of Reduced Coefficients

Shift sampling interval 14 time steps to the left, to the start of the transients. This will give an indication if the spectral response changed.

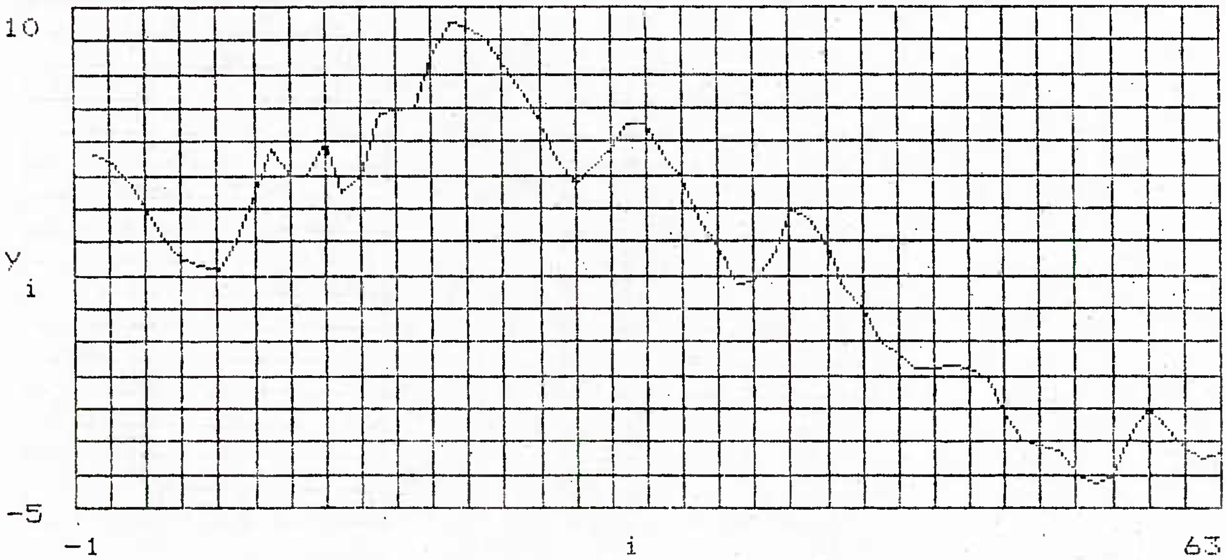
$$i := 0 \,..\, 13 \qquad y_i := \begin{array}{|c|}\hline 5.6\\\hline 5.5\\\hline 4.8\\\hline 4.\\\hline 3\\\hline 2.5\\\hline 2.3\\\hline 2.1\\\hline 3\\\hline 4.5\\\hline 5.8\\\hline 5\\\hline 5\\\hline 6\\\hline\end{array}$$

$$i := 14 \,..\, 63$$

$$y_i := x_{i-14}$$

$i := 0 \,..\, 63$

Graph of Shifted Sample Interval



Now do fft of shifted samples.

$z := \mathrm{fft}(y)$

$N := \mathrm{last}(z) \qquad N = 32$

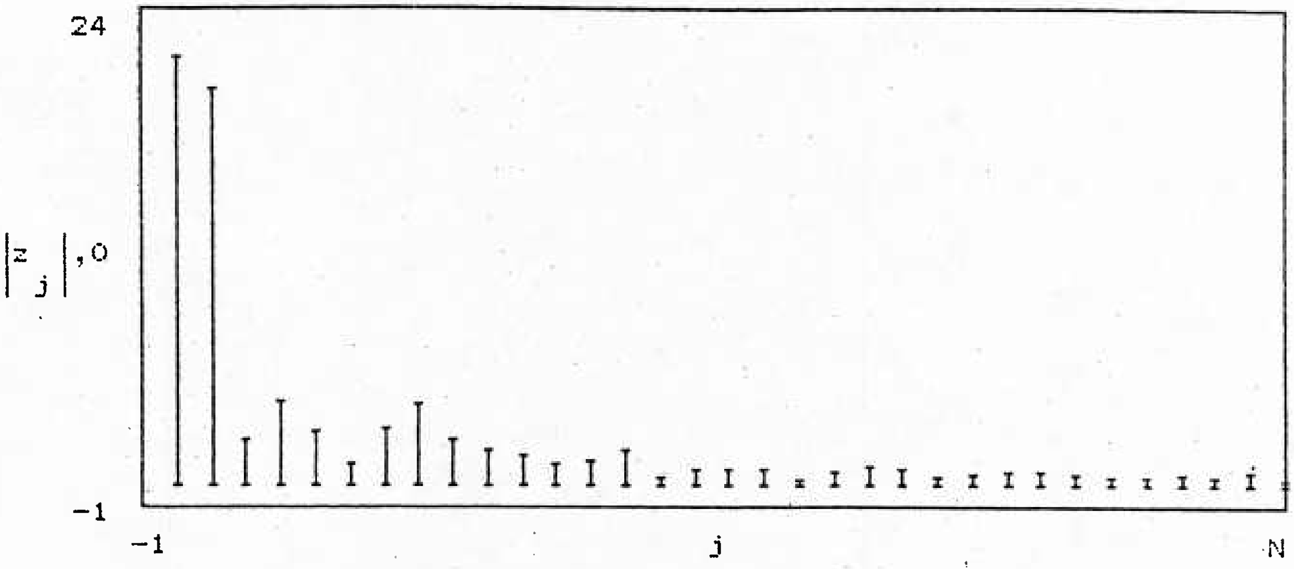
$j := 0 \,..\, N$

Table of Results

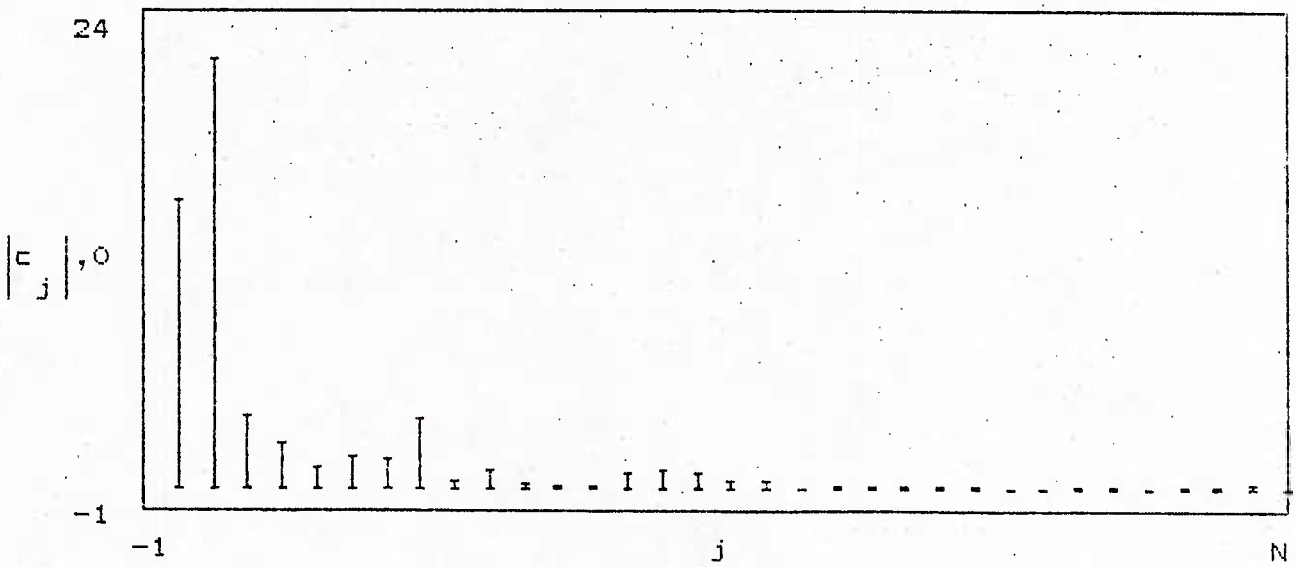
Coefficients

	Original Sample	Shifted Sample
j	c_j	z_j
0	14.5	21.513
1	10.891 + 18.596i	-10.265 + 17.061i
2	2.721 + 2.492i	-0.116 + 2.428i
3	-0.632 + 2.339i	3.792 + 1.911i
4	-0.752 + 0.922i	1.455 + 2.404i
5	-1.257 + 1.174i	0.516 + 1.052i
6	-1.509 + 0.37i	2.973 - 0.067i
7	2.844 - 2.306i	-0.973 + 4.016i
8	0.496 + 0.029i	1.329 + 1.939i
9	-0.959 - 0.347i	-0.344 + 1.747i
10	0.078 + 0.334i	0.344 + 1.523i
11	0.025 + 0.173i	0.725 + 0.98i
12	0.2 + 0.029i	0.816 + 1.027i
13	0.742 + 0.47i	1.613 + 0.951i
14	-0.537 - 0.866i	0.387 + 0.309i
15	-0.778 - 0.417i	0.816 + 0.481i
16	-0.512 + 0.112i	0.55 + 0.713i
17	-0.425 - 0.205i	-0.058 + 0.839i
18	-0.111 - 0.003i	0.264 + 0.116i
19	-0.174 - 0.132i	0.751 - 0.109i
20	0.037 - 0.179i	0.956 + 0.53i
21	0.018 - 0.274i	0.5 + 0.76i
22	-0.088 - 0.246i	0.193 + 0.401i
23	0.117 - 0.095i	0.619 + 0.098i
24	0.054 - 0.046i	0.746 + 0.164i
25	0.021 + 0.069i	0.766 + 0.215i
26	0.138 - 0.142i	0.475 + 0.35i
27	0.148 - 0.136i	0.507 + 0.153i
28	-0.035 - 0.037i	0.423 + 0.108i
29	-0.217 + 0.127i	0.535 - 0.179i
30	0.009 - 0.177i	0.481 + 0.273i
31	0.237 + 0.183i	0.7 - 0.08i
32	-0.075	0.337

Coefficients of z



Coefficients of c



The low value of the 2nd harmonic (3rd coefficient) in both of the samples indicates that there is no significant effect even during the initial transients.

APPENDIX C
COST ESTIMATE WORK SHEETS

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER
BLACK & VEATCH

BASIS FOR ESTIMATE

☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO.

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		~~LABOR~~		~~MATERIAL~~		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	~~TOTAL~~ METHOD I	PER UNIT	~~TOTAL~~ METHOD VI	
✓ TUBE + FLANGE			✓	94600	✓	94600	
HEATING SYSTEM				50 000		50000	
INSULATION SYSTEM				37000		37000	
TUBE COOLING SYSTEM				10500		10500	
✓ VALVE/DIAPH COOLING			✓	10200	✓	10200	
✓ ANCHOR SYSTEM			✓	37800	✓	49500	
✓ 3FT TUBE SUPPORTS			✓	21000	✓	19600	
3FT TUBE GROUND SUPPORTS				—		5250	
8FT TUBE GROUND SUPPORTS				5250		—	
✓ REACTION BLOCK REPAIR			✓	18320	✓	18320	
✓ 3FT TUBE INSTALLATION			✓	110,000	✓	48000	
WEATHER COVER				—	✓	24300	
SUB TOTAL				394170		366770	
15% CONTINGENCY				59126		55016	
TOTAL				453,296		421,786	

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER BLACK & VEATCH

BASIS FOR ESTIMATE
☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO.

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
VAPORIZER + PUMP	2	LS	9000	18000	18000	36000	
METAL BUILDING 200FT	1	LS		4000		4000	
PIPING 50' 1" STAINLESS		LS		1000		500	
SCHED 40 INSULATED							
PIPING 200' 3" STAINESS		LS		3000		2000	
SCHED 160							
BOOSTER HEATER	1	LS		5000		5000	
MARKUP				x1.5		x1.25	
				46500		59375	105875
						USE	106,000
						106,000	
15% CONTINGENCY						15900	
						121,900	

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER BLACK & VEATCH

BASIS FOR ESTIMATE
☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO.

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
QUICK VALVE							
DEVELOPEMENT		LS				50,000	
18" PROTOTYPE		LS				380 000	
COMPUTER		LS				15000	
VALVE SUPPORT						3000	
TRANSITION TO 8 FT						8000	
SUBTOTAL						456000	
15% CONTINGENCY						68400	
TOTAL						524400	

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER
BLACK & VEATCH

BASIS FOR ESTIMATE
☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO.

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
DIAPH MOUNT						24400	
TRANSITION						8000	
SUBTOTAL						32400	
15% CONTINGENCY						4860	
TOTAL						37260	

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER

BASIS FOR ESTIMATE

☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO. Method 1 & 6

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
<u>3'φ Driver Tube</u>							
<u>& Flange</u>							
3'φ High Pressure							
Driver Tube 80'	74000	LB			1.00	74000	
HEAD	2000	LB			3.00	6000	
FLANGE	2000	LB			3.00	6000	
						86,000	
						× 1.10	
						94,600	

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

BASIS FOR ESTIMATE
☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

ARCHITECT ENGINEER BLACK & VEATCH

DRAWING NO. METHOD 1 + 6

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
INSULATION SYSTEM							
12" INSULATION	1360	FT^2	4.00	5440	17.00	23120	
MARK UPS				X1.5		X1.25	
				8160		28900	37,060
						USE	37,000
HEATING SYSTEM							
30 KW OF HEATER	40	U	75	3000	200	8000	
30 KW OF SWITCHGEAR							
& WIRING	30	KW	150	4500	200	6000	
INSTR + CONTR							
20 POINTS	20	PT	300	6000	500	10000	
MARK UP			X	1.5		X1.25	
				20,250		30000	50,250
						USE	50,000
TUBE COOLING							
BLOWER		LS		1500		5000	
BLIND FLANGE		LS		50		1100	
				X1.5		X1.25	
				2327		7625	9952
						USE	10000

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER

BASIS FOR ESTIMATE
☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO. Method 1 & 6

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
VALVE/DIAPH Cooling							
System							
Closed Cycle	1	LS		3700		3700	
Mark-up				x1.5		x1.25	
				5550		4625	10,175
							Say
							10,200

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER

BASIS FOR ESTIMATE

☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO. Method 1

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
<u>Anchor</u>							
Removable Flange	1	EA		2500		20 000	
Carriage For Removable Flange	1	EA		450		4,500	
Foundation For Flange Carriage	1	EA		1000		1000	
				3950		25,500	
Mark-ups				x 1.5		x 1.25	
				5925		31875	37,800

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER

BASIS FOR ESTIMATE
☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO. Method 6

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
Anchor							
Addition to Reaction Pier –							
Concrete	33	CY	100^{00}	3300	150^{00}	4950	
Struct. Stl.	3.8	Ton	500^{00}	1900	1500^{00}	5700	
Thrust & Collar Rings	1	LS		1100		11000	
Rebound Ring	1	LS		930		9300	
				7230		30,950	
				x 1.5		x 1.25	
				10,845		38,688	49,533
							Say
							49,500

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER

BASIS FOR ESTIMATE

☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO. Method 1

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
3'ϕ Tube Supports							
Support Trucks	1	LS		400		16,200	
Mark-ups				x 1.5		x 1.25	
				600		20250	20,850 Say
							21,000

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER BLACK & VEATCH

BASIS FOR ESTIMATE

☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO. METHOD 1 & 6

ESTIMATOR

CHECKED BY

	QUANTITY		LABOR		MATERIAL		
SUMMARY	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	TOTAL COST
Reaction Pier Repair							
Fabricated Stl. Plate	9250	LB	$0^{\underline{10}}$	925	$1^{\underline{00}}$	9250	
3/4"x6" Stl. Bar	740	LB	$0^{\underline{10}}$	74	$0^{\underline{50}}$	370	
Grout	302	SF	$0^{\underline{37}}$	112	$0^{\underline{39}}$	118	
3/8" Butt Weld	48	LF	$10^{\underline{30}}$	494	$0^{\underline{66}}$	32	
"Z" Furring Channel	50	LF	$1^{\underline{00}}$	50	$0^{\underline{25}}$	13	
Expansion Bolts 3/8"	24	EA	$2^{\underline{00}}$	48	$0^{\underline{50}}$	12	
3/8" Fillet Weld	24	LF	$5^{\underline{15}}$	124	$0^{\underline{33}}$	8	
Chip Conc.	16	MH	$25^{\underline{00}}$	400			
Grout Cracks	16	MH	$25^{\underline{00}}$	400		200	
Grout Equipment	1	Day				1500	
				2627		11,503	
Markups				x 1.5		x1.25	
				3941		14,379	18,320

ENG FORM 150

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

BASIS FOR ESTIMATE
☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

ARCHITECT ENGINEER
BLACK & VEATCH

DRAWING NO.
Method 1

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY NO. UNITS	QUANTITY UNIT MEAS.	LABOR PER UNIT	LABOR TOTAL	MATERIAL PER UNIT	MATERIAL TOTAL	TOTAL COST
8'φ Tube New Supports &							
Foundations 6	Units						
Concrete (In Place)	12	CY	59^{00}	708	80^{00}	960	
30# Rail	36	LF	5^{00}	180	4^{00}	144	
Excavation - Hand	42	CY	15^{90}	668			
Remove Ties	18	EA	10^{00}	180			
Remove Track	1	LS		360			
Backfill & Compact	30	CY	16^{75}	503			
				2599		1104	
Mark-up				x 1.5		x 1.25	
				3899		1380	5279
						USE	5250

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER

BASIS FOR ESTIMATE

☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO. Method 1

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
3'φ Tube Installation							
Offload Tube @ R.R. Siding and Truck to Site	1		EA	1200			
8' Tube Shoring	1	LS		10000		20,000	
Track	1	LS		4700		12750	
Install Winch & Pull New 3'φ Driver Tube into Position	60	MH	25^00	1500		5,000	
Piping Connections	1	LS		5000		5000	
Electrical Connections	1	LS		5000		5000	
Truck Rental	1	WK			1500	1500	
Crane Rental	2	WKS			3000	6000	
				27,400		55,250	
				x 1.5		x 1.25	
				41100		69063	110163
							say 110,000

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER

BASIS FOR ESTIMATE

☐ CODE A *(No design completed)*
☐ CODE B *(Preliminary design)*
☐ CODE C *(Final design)*
☐ OTHER *(Specify)*

DRAWING NO. Method 6

ESTIMATOR

CHECKED BY

	QUANTITY		LABOR		MATERIAL		TOTAL COST
SUMMARY	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
3'ϕ Tube Supports							
Struct Stl.	9.0	Ton	200^{00}	1800	1500^{00}	13,500	
Mark-up				x1.50		x1.25	
				2700		16,875	19,575
							Say
							19,600

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER BLACK & VEATCH

BASIS FOR ESTIMATE
☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO. Method 6

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY NO. UNITS	QUANTITY UNIT MEAS.	LABOR PER UNIT	LABOR TOTAL	MATERIAL PER UNIT	MATERIAL TOTAL	TOTAL COST
3'ϕ Tube New Supports & Foundations	6	Units					
Concrete (In Place)	12	CY	59^{00}	708	80^{00}	960	
30# Rail	36	LF	5^{00}	180	4^{00}	144	
Excavation - Hand	42	CY	15^{90}	668			
Remove Ties	18	EA	10^{00}	180			
Remove Track	1	LS		360			
Backfill & Compact	30	CY	16^{75}	503			
				2599		1104	
Mark-up				x 1.5		x 1.25	
				3899		1380	5279
						USE	5250

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER

BASIS FOR ESTIMATE

☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO. Method 6

ESTIMATOR

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SUMMARY	QUANTITY NO. UNITS	QUANTITY UNIT MEAS.	LABOR PER UNIT	LABOR TOTAL	MATERIAL PER UNIT	MATERIAL TOTAL	TOTAL COST
3'φ Tube Installation							
Construct Laydown Area	1000	SF	0^{15}	150	0^{40}	400	
Offload Tube @ R.R. Siding and Truck to Site	1	EA		1200			
Torch Cut 8'φ Tube	25	LF	16^{00}	400			
Unbolt 8'φ Driver from Reaction Pier	1	EA		400			
Remove 85' Section of Tube 11 Men x 1 Day	98	MH	25^{00}	2450			
Crane Rental	2	Wks			3000^{00}	6000	
Tractor Trailer	1	Wk			1500^{00}	1500	
Install 3'φ Tube	100	MH	25^{00}	2500			
Piping Connections	1	LS		5000		5000	
Electrical Connections	1	LS		5000		5000	
				17,100		17,900	
Mark-up				x 1.50		x 1.25	
				25,650		22,375	48,025
							Say

48,000

CONSTRUCTION COST ESTIMATE

DATE PREPARED

SHEET OF

PROJECT

LOCATION

ARCHITECT ENGINEER

BASIS FOR ESTIMATE

☐ CODE A (No design completed)
☐ CODE B (Preliminary design)
☐ CODE C (Final design)
☐ OTHER (Specify)

DRAWING NO. Method 6

ESTIMATOR

CHECKED BY

SUMMARY	QUANTITY		LABOR		MATERIAL		TOTAL COST
	NO. UNITS	UNIT MEAS.	PER UNIT	TOTAL	PER UNIT	TOTAL	
Weather Cover							
Pre-engineered							
Metal Bldg Rigid							
Frame including							
Steel Siding & Trim &							
Foundation	1800	SF	1^{50}	2700	9^{00}	16,200	
Mark-up				x 1.5		x 1.25	
				4050		20,250	24,300

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