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AETRON®

COVINA, CALIFORNIA

PHOEBUS TEST FACILITY
PROPOSED TURBINE DRIVE SYSTEM
CONVERTING LIQUID TO HOT GAS

MAY 1965

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Technical Information

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PHOEBUS TEST FACILITY
PROPOSED TURBINE DRIVE SYSTEM
CONVERTING LIQUID TO HOT GAS

PREPARED BY
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I. INTRODUCTION

The cost of gas storage capacity for hot GH_2 testing of components becomes prohibitive when runs are of long duration and it is more economical to provide the additional heating capacity to heat LH_2 . This proposal is for the necessary facilities to supply hot GH_2 at a rate of 25 pounds per second, and at a temperature of $1,400^\circ\text{R}$ for a duration of 20 minutes from liquid hydrogen. The layout shown is somewhat generalized, as are the lengths of connecting lines. Development of the design will produce changes consistent with the site conditions to be met.

II. SCOPE

This proposal based on rough calculations and estimates includes all the necessary facilities for storage, boosting pressure, and heating, together with all auxiliary equipment and tie-ins to existing lines. The hot GH_2 line is assumed to be 125 feet long. LH_2 storage, GH_2 storage, and deluge water are assumed to be available within 100 feet. The GH_2 storage is assumed to be sufficient for pressurizing the liquid vessel and for starting the turbo-pump, using five pounds per second for five seconds.

The LH_2 storage will comprise a 70,000 gallon vacuum jacketed vessel, pressurizing line, liquid line, and valves and controls.

The pressure boost will be by means of a turbo-pump assembly driven by GH_2 .

The heating system will consist of a direct propane-fired heater with fuel tank, fuel vaporizer, piping, and combustion air blower and ducting.

III. DESIGN CONSIDERATIONS

The required output pressure will be generated by pumping the LH_2 to a pressure of up to 800 psi. The equipment used for this will be a turbo-pump assembly driven by GH_2 at approximately ambient temperature and 500 psi. This makes necessary a supply of GH_2 for starting to the point where the output pressure is sufficient to drive the turbine after being heated. For supplying the drive gas for running, several choices are possible:

- (1) A separate heater for preheat to 510°R .
- (2) A tap for 510°R gas in the main heater.
- (3) Diversion of sufficient gas at the output temperature to mix with liquid and produce the required 510°R gas.

Number (3) was chosen as offering the simplest control and simplest construction.

Temperature control of the output requires control of the firing rate. However, response to fire control is relatively slow. In order to obtain rapid response, liquid will be injected into the hot gas output of the heater to control the temperature of the gas in the discharge line to the test. The firing rate will be controlled to maintain a constant temperature in the heater tubes.

The LH_2 lines will be vacuum jacketed up to the pump inlet in order to deliver pure liquid to the pump.

The LH_2 vessel has a capacity sufficient for one 20 minute run at 30 pounds per minute total consumption. The fuel tank has a capacity sufficient for approximately one hour's firing.

Pressure control of the hot gas will be effected by varying the liquid pressure and this will be controlled by throttling of the driving gas supply to the turbine.

Hot gas lines will be insulated to conserve heat and protect operating personnel.

IV. COST

Cost of the turbo-pump assembly has not been included in the cost of this project. It is assumed that a modified Phoebus turbo-pump can be used and will be available.

Cost of the hydrogen heater and equipment directly connected with it, such as combustion air blower and ducting, burners, controls, propane vaporizer, etc. has not been reduced to a detailed estimate, since this would involve design work beyond the scope of this report. Instead, the cost has been estimated by directly scaling up the actual installed cost of the Nerva heater at Aerojet-General Corporation's Sacramento plant. This amounts to approximately \$2,300 per million BTU's per hour net heat output. This appears to be slightly conservative in view of the lower temperature, but a minimum safe figure for budgeting.

Instrumentation cables have been estimated on the basis of a distance of 2,500 feet and assuming existing trenches or conduits are available. No receiving instruments have been included.

The estimated cost to a rough order of magnitude is \$1,400,000.

PROJECT Nerva SUBJECT LH₂ Heater System
 LOCATION _____
 PLANT _____ BY Drew CHECKED _____

PAGE 1 OF _____
 DATE 4-23-65

LH₂ requirement

$$30 \text{ lb/sec for } 20 \text{ min} = 30 \times 20 \times 60 = 36,000 \text{ lb}$$

$$\text{Min vessel capacity} = \frac{36,000}{0.9 \times 0.585} = 68,400 \text{ gal}$$

$$\frac{68,400}{7.48} = 9150 \text{ cu ft} = \frac{4}{3} \pi R^3$$

$$R^3 = 2185$$

$$R = 13 \text{ ft}$$

outer 39' 4" dia
 3 ft

20000 gal
 57500 ft
 10000 gal
 10000 gal
 10000 gal
 10000 gal
 10000 gal
 10000 gal

Heat requirement

Tabulated enthalpy values to 540°R

$$\text{Work of pumping, net} = \frac{780 \times 144}{778} = 144 \text{ Btu/cuft}$$

$$144 \times 0.2166 = 31.2 \text{ Btu/lb.}$$

$$\text{Assuming 60\% eff., waste heat} = 0.4 \times 31.2 = 12.5 \text{ Btu/lb.}$$

State of H₂ entering heater corresponds to pressure increase from 20 to 800 psia at constant entropy, then addition of 12.5 Btu/lb.

$$-75 + 12.5 = -62.5 \text{ Btu/lb.}$$

PROJECT Nerva SUBJECT LH₂ Heater System
 LOCATION _____
 PLANT _____ BY Drew CHECKED _____

PAGE 2 OF _____
 DATE 4-30-65

At 540°R H = 1815

Inlet H = -62.5

1877.5

$$1400 - 540 = 860^\circ$$

$$\text{At } C_p = 3.5, \text{ heat} = 3.5 \times 860 = 3010 \text{ Btu/lb}$$

$$\text{Total heat added} = \frac{1877}{4887} \text{ Btu/lb}$$

For 25 lbs per sec, heat output =

$$25 \times 4887 = 122,200 \text{ Btu/sec}$$

$$122,200 \times 60 = 7,332,000 \text{ Btu/min}$$

$$122,200 \times 3600 = 440,000,000 \text{ Btu/hr}$$

$$\text{Assuming 50\% eff, input} = \frac{880,000,000 \text{ Btu/hr}}{50\%}$$

Turbine supply 5 lb/sec @ 510°R

$$H = 1707$$

$$- 62.5$$

$$1769.5$$

$$5 \times 1769.5 = 8850 \text{ Btu/sec} = 31,800,000 \text{ Btu/hr}$$

$$\text{Input} = 2 \times 31,800,000 = 63,600,000 \text{ Btu/hr input}$$

$$\text{Total heater input} = 940,600,000 \text{ Btu/hr}$$

$$\text{Propane use @ } 19,766 \text{ Btu/lb} = 47,600 \text{ lb/hr}$$

$$\text{Vol. gas} = \frac{47,600}{0.114} = 418,000 \text{ ft}^3 = 15,900 \text{ lb for 20 min}$$

PROJECT Nerva SUBJECT LH₂ Heater System
 LOCATION _____
 PLANT _____ BY Drew CHECKED _____

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 DATE 5-3-65

Turbine supply

Assume hot gas taken from heater discharge
 and mixed with liquid

Heat supplied = 8850 Btu/sec (p. 2)

$$\text{Quantity of hot gas} = \frac{8850}{4887} = 1.81 \text{ lb/sec}$$

$$\text{Quantity of liquid} = 5 - 1.81 = 3.19 \text{ lb/sec}$$

Design hot gas line for 5 lb/sec @ 510°R,
 600 psi P₁, and 100 psi ΔP

Design liquid line for 3.2 lb/sec

$$\text{Try 1" Sch 10S } d = 1.097, d^4 = 1.448 \quad D = 0.0914$$

$$\text{Assume 30 ft pipe } K = 0.023 \times \frac{30}{0.0914} = 7.55$$

$$\text{Assume 6 elbows @ 13 dia } K = 0.023 \times 6 \times 13 = 1.79$$

$$\text{Globe valve } K = \frac{891 \times 1.448}{12^2} = 8.96$$

$$\text{Control valve - assume same as globe} = 8.96$$

$$\Delta P = 0.000000280 \times \frac{27.26 \times 3.2^2 \times 3600^2}{1.448 \times 4.5} = 157 \text{ psi}$$

OK

PROJECT _____ SUBJECT LH₂ Heater System
 LOCATION _____ PAGE 4 OF _____
 PLANT _____ BY Drew CHECKED _____ DATE 5-6-65

Liquid fuel line $W = 47,600 \text{ #/hr}$ $V = 0.03269$

Try 2" Sch 40 $d = 2.067"$ $D = 0.1722'$ $d^4 = 18.250$

Assume 150ft pipe; $K = 0.019 \times \frac{150}{0.1722} = 16.5$

Assume 5 elbows @ 13 dia $K = 0.019 \times 13 \times 5 = 1.2$

Assume 2 valves @ 300 dia $K = 0.019 \times 2 \times 300 = 11.4$

29.1

$$\Delta P = 0.000000280 \frac{KW^2 V}{d^4}$$

$$= 0.000000280 \times \frac{29.1 \times 47,600^2 \times 0.03269}{18.25} = 33.1 \text{ psi}$$

O.K.

Gaseous fuel line - assume 80ft.

Assume 10 psig $P = \frac{25 \times 144}{35 \times 540} = 0.1905 \text{ lb/cuft}$

Try 4" Sch 40 $d = 4.026"$ $d^4 = 262.76$ $D = 0.3355'$

80ft pipe $K = 0.016 \times \frac{80}{0.3355} = 3.81$

1 valve @ 300 dia $K = 0.016 \times 300 = 4.80$

4 elbows @ 13 dia $K = 0.016 \times 52 = 0.83$
9.44

Assuming small ΔP , try above formula

$$\Delta P = 0.000000280 \times \frac{9.44 \times 47,600^2}{262.76 \times 0.1905} = 120 \text{ psi}$$

too high

PROJECT _____ SUBJECT LH₂ Heater System
 LOCATION _____ PAGE 5 OF _____
 PLANT _____ BY Drew CHECKED _____ DATE 5-6-65

Fuel gas line, cont.

Try 6" Sch 40 $d = 6.065$ $d^4 = 1352.8$ $D = 0.5054$

80ft pipe $K = 0.015 \times \frac{80}{0.5054} = 2.37$

1 valve @ 300 dia $K = 0.015 \times 300 = 4.5$

4 elbows @ 13 dia $K = 0.015 \times 52 = .78$

7.65

$\Delta P = \frac{0.000000280 \times 7.65 \times 47,600^2}{1352.8 \times 0.1905} = 18.8 \text{ psi}$
too high

Try 8" Sch 30 $d = 8.071$ $d^4 = 4243$ $D = 0.6726$

$K = \frac{0.014}{0.015} \times 7.65 = 7.14$

$\Delta P = \frac{0.000000280 \times 7.14 \times 47,600^2}{4243 \times 0.1905} = 5.6 \text{ psi}$
OK.

Hot GH₂ line 1400°R, 500psig, 25 lb/sec
940°F

125ft line $S = 13,900 \text{ psi allowable}$
for 321 stainless

$C = \frac{500 \times 144}{1400 \times 767} = 0.067$

Try 8" $t = \frac{PD_0}{2(SE + PY)} = \frac{500 \times 8.625}{2(13900 + 0.4 \times 500)} = 0.153$
₁₂₀₀
₁₄₁₀₀

$t_m = \frac{0.153}{0.875} = 0.175 \text{ in. min.}$

Sch 20 $d = 8.125$ $d^4 = 4359$ $D = 0.6771$

$W = 25 \times 36.00 = 90,000 \text{ lbs/hr}$

PROJECT _____

SUBJECT

LH₂ Heater System

LOCATION _____

PAGE 6 OF _____

PLANT _____

BY

Drew

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DATE

5-6-65

Hot GH₂ line - 8" cont

$$125 \text{ ft} \quad K = 0.014 \times \frac{125}{0.6771} = 2.58$$

$$\text{Assume 4 elbows @ 13 dia } K = 0.014 \times 52 = 1.72$$

$$\underline{3.30}$$

$$\Delta P = \frac{0.000000280 \times 3.30 \times 90,000^2}{4359 \times 0.067} = 25.6 \text{ psi}$$

O.K.

PROJECT Meriva SUBJECT LH₂ Heater System
 LOCATION _____ Line Sizes PAGE 7 OF _____
 PLANT _____ BY Drew CHECKED _____ DATE 5-5-65

LH₂ - vessel to pump

Assume

$$L = 125 \text{ ft}$$

$$\Delta P = 50 \text{ psi max}$$

$$d = 4.26$$

(4" sch 10S)

$$w = 30 \text{ lb/sec}$$

$$W = 108,000 \text{ lb/hr}$$

$$P = 4.4$$

$$\bar{V} = \frac{1}{4.4}$$

$$K = \frac{0.016 \times 125}{0.4413} = 4.58$$

$$\Delta P = 0.000000280 \frac{KW^2 \bar{V}}{d^4}$$

$$= \frac{0.000000280 \times 4.58 \times 108,000^2}{329.3 \times 4.4} = 10.32 \text{ psi}$$

Try 3" sch 10S $d = 3.26$ $d^4 = 112.9$ $A = 0.5796$
 $D = 0.2717$

$$K = \frac{0.017 \times 125}{0.2717} = 7.82$$

$$\Delta P = \frac{0.000000280 \times 7.82 \times 108,000^2}{112.9 \times 4.4} = 51.5 \text{ psi}$$

Use 4"

PROJECT _____ SUBJECT LH₂ Heater System
 LOCATION _____ PAGE 8 OF _____
 PLANT _____ BY Drew CHECKED _____ DATE _____

GH₂ Supply Line - Base on starting requirement
 of 5 lb/sec. Assume 2000 psi in, 500 psi out
 $P = 0.66$ $\Delta P = 1500$ psi $\frac{\Delta P}{P_i} = 0.75$

Assume $L = 125$ ft

Try 3" X XS $d = 2.30$ $d^2 = 5.29$ $D = 0.1917$ $d^4 = 27.98$

$$125 \text{ ft. pipe } K = 0.0185 \times \frac{125}{0.1917} = 12.05$$

$$8 \text{ elbows @ } 13 \text{ dia } K = 0.0185 \times 8 \times 13 = 1.92$$

$$\text{Filter @ } 200 \text{ dia } K = 0.0185 \times 200 = 3.70$$

$$\text{Regulator @ } 200 \text{ dia } K = 3.70$$

$$\text{Control valve } C_v = 76 \quad K = \frac{891 \times 27.98}{76^2} = 4.30$$

$$K = 25.67$$

$$W = 0.525 Y d^2 \sqrt{\frac{\Delta P P}{K}} \quad Y = 0.75$$

$$W = 0.525 \times 0.75 \times 5.29 \sqrt{\frac{1500 \times 0.66}{25.67}} = 12.9 \text{ lb/sec}$$

Try 2" X XS $d = 1.503$

Approx. flow capacity prop. to $d^{\frac{5}{2}}$

$$W = \left(\frac{1.503}{2.30} \right)^{\frac{5}{2}} \times 12.9 = 4.45 \text{ lb/sec marginal}$$

use 3"

PROJECT Nerva SUBJECT LH₂ Heater System
 LOCATION _____
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 DATE 4-23-65

Water deluge coverage

LH₂ dewar

A Vent & relief valve manifold & piping
 0.4 gpm per sq ft of platform area

$$0.4 \times 60$$

B Upper half of sphere

3 gpm per ft of periphery at equator

$$3 \times 34 \pi =$$

24 gpm

352

C Lower half of sphere - 0.4 gpm/sq ft

$$0.4 \times 34^2 \times \frac{\pi}{2}$$

720

Furnace - assume 60 ft long, 20 ft high
 @ 0.4 gpm per sq ft of sides

$$2 \times 60 \times 20 \times 0.4$$

1096 gpm

960 gpm

Fuel tank - assume 50 ft long X 6 ft dia
 @ 0.4 gpm per sq ft of ground area

$$0.4 \times 50 \times 6$$

120 gpm

2176

With misc. additional, say 2500 gpm

Pipe sizes - allow 5-10 psi per 100 ft.

1096 gpm - 8"

960 " - 8"

120 " - 3"

2176 " - 10"

PROJECT Mervin SUBJECT LH₂ Heater System
 LOCATION _____
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Estimate of furnace dimensions

Scale up size of Sacramento heater on the following basis:

Use same height

Make header lengths in proportion to volumetric flow rate at discharge $\times \sqrt{\text{density}}$

Make volume of furnace in proportion to net heat input.

Volumetric rate of discharge - 30 lb/sec @ 1400°R

$$P = \frac{500 \times 144}{767 \times 1400} = 0.0671$$

$$q' = \frac{30}{0.0671} = 447 \text{ cfs}$$

Rate for Sacto heater - 10 lb/sec @ 1810°R, 900 psi

$$P = \frac{900 \times 144}{767 \times 1810} = 0.0933$$

$$q' = \frac{10}{0.0933} = 107 \text{ cfs} \quad \text{length of heater} = 25 \text{ ft}$$

$$\text{Scale length} = 25 \times \frac{447}{107} \sqrt{\frac{0.0671}{0.0933}} = 88.6 \text{ ft}$$

It is not practical to fire such a distance.
 Make length = 40 ft. - say 65 ft overall

PROJECT Nerva SUBJECT LH₂ Heater System
 LOCATION _____
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$$\text{Width} = \frac{504,000,000 \times 25 \times 21.2}{173,000,000 \times 40} = 38.6 \text{ ft}$$

say 40 ft outside

Fuel tank - fuel for 3 runs of 20 min. = 1 hr.
 Estimated use = 47,600 lb.

$$\text{Volume} = \frac{47,600}{31.57} = 1510 \text{ cu ft.}$$

$$\text{Ullage } 10\% = \frac{151}{1661} \text{ cu ft.} = d^2 \pi L$$

$$\text{Try } d = 10 \text{ ft}$$

$$L = \frac{16.61}{.7854} = 21.2 \text{ ft.}$$

$$\text{Try } d = 8 \text{ ft}$$

$$L = \frac{16.61}{64 \times 0.7854} = 33 \text{ ft} - \text{say } 36 \text{ ft overall}$$

$$\text{Gallon rating} = 1661 \times 7.48 = 12,400 \text{ gal.}$$

PROJECT Mervia SUBJECT LHz Hester System
 LOCATION _____
 PLANT _____ BY Drew CHECKED _____

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 DATE 5-3-65

Combustion air $-0.239 \times$ propane by volume

Allow 20% excess

$$\text{Vol. air} = 1.20 \times 23.9 \times 418,000 = 12,000,000 \text{ CFH} \\ = 200,000 \text{ CFM}$$

Extrapolate from tables by Master Fan
 from $5\frac{1}{2}$ " W.C. to 8" W.C.

$$\text{Speed ratio} = \sqrt{\frac{8}{5.5}} = 1.206 = \text{CFM ratio}$$

$$\frac{200,000}{1.206} = 166,000$$

#11 DIDW Type FCD

$$\text{Horse power} = 1.206^3 \times 243 = 425$$

$$\text{RPM} = 351 \times \frac{8}{5.5} = 511$$

Type BCD #11 DIDW

Extrapolate from 2" W.C. 100,000 CFM

$$\text{BHP} = 8 \times 46.69 = 373 \text{ hp}$$

$$\text{RPM} = 2 \times 416 = 832$$

PROJECT _____

SUBJECT

LH2 Heater System

LOCATION _____

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BY

Drew

CHECKED _____

DATE

5-20-65

Turbine exhaust line to stack - assume 125 ft.

For adiabatic expansion from 500 psi @ 510°R

$$\text{to 25 psi, } T_2 = T_1 \left(\frac{P_2}{P_1} \right)^{\frac{k-1}{k}} =$$

$$510 \left(\frac{25}{500} \right)^{\frac{0.4}{1.4}} = 217^\circ\text{R}$$

Even with inefficiency, Temperature is too low for carbon steel pipe.

$$\text{Assume } T_2 = 300^\circ\text{R} \quad C = 0.015$$

$$\text{Try 6" Sch 10S } d = 6.357 \quad d^2 = 40.41 \quad D = 0.5298$$

Assuming equivalent 150 ft length

$$K = 0.015 \times \frac{150}{0.5298} = 4.25$$

$$\frac{\Delta P}{P_1} = 0.67 \quad Y = 0.67$$

$$W = 0.525 \times 0.67 \times 40.41 \sqrt{\frac{10 \times 0.015}{4.25}} = 2.67 \text{ lb/sec}$$

$$\text{Try 8" Sch 10S } d = 8.329 \quad d^2 = 69.37 \quad D = 0.6941$$

$$K = 0.014 \times \frac{150}{0.6941} = 3.03$$

$$W = 0.525 \times 0.67 \times 69.37 \sqrt{\frac{10 \times 0.015}{3.03}} = 5.41 \text{ lb/sec.}$$

OK.

CUSTOMER		LOCATION		PHEBUS TEST FACILITY	
WORK		TURBINE DRIVE SYSTEM CONVERTING LH2 TO HOT GH2		GROUP	
DRAWING		BY		DATE	
ITEM		QUANTITY	UNIT	UNIT COST MAT'L LABOR	MATERIAL COST LABOR COST
HYDROGEN HEATER INSTALLED, INCLUDING FUEL VAPORIZER, AIR SUPPLY, CONTROLS, AND ALL EQUIPMENT.		440 MILLION	BTU/HR	2300	1,012,000
70,000 GAL. VACUUM JACKETED LH2 VESSEL 100 PSIG		1 EA			220,000
3" VACUUM JACKETED PIPING-VG SPEC. SCH. 10S		125 FT		100 -	12,500
4" DITTO		125 FT		120 -	15,000
8" STAINLESS PIPING SPEC. H SCH. 40 WITH 1000°F INSULATION		125 FT		90 -	11,250
3" GH2 FILTER 6000 PSI		1		5000 -	5000
3" GH2 REGULATOR 6000 PSI TO 500 PSI		1		2500 -	2500
3" STAINLESS STEEL CONTROL VALVE 300# ASA		2		4000 -	8000
1 1/2" DITTO		2		2000 -	4000
1" DITTO		1		1500	1500
3" RSV - STAINLESS 300 ASA		2		3000 -	6000
8" RSV 150# ASA WATER		1		1000	1000
10" CS PIPING 1/2" WALL		125 FT		1500	1875
8" DITTO		200 FT		1200	2400
3" GALV. PIPING SCH 40		200 FT		80 -	1600
12,500 GAL. STORAGE VESSEL 250 PSI		1		1000	11000
2" CS PIPING SCH 40		120	FT	3	360
MISC. SMALL PIPING & FITTINGS					5000
PIPE SUPPORTS & MISC					5000
TOTAL					1328490

CUSTOMER		LOCATION PHEBUS TEST FACILITY					
WORK TURBINE DRIVE SYSTEM CONVERTING LH ₂ TO HOT GH ₂		GROUP					
DRAWING		BY		DATE 5-19-65			
I T E M	QUANTITY	UNIT	UNIT COST		MATERIAL COST	LABOR COST	
			MAT'L	LABOR			
16" FLARE STACK	1				14000	5000	19000
8" SCH 10S SS PIPING	125	FT	50				6250
4X6 SS RELIEF VALVE	1		2000				2000
INSTRUMENTATION							
PRESSURE TRANSDUCER	1	EA	500		500	200	700
TEMP. TRANS	3	EA	350		1050	500	1550
CABLE	2500	FT					2500
POWER SUPPLY FOR BLOWER							
AREA LIGHTING							
GRADING ACCESS, & MISC. STRUCTURES							
BRT. FWD. FROM PAGE 1							
TOTAL		ROM \$1,400,000				1387490	

88-067-121

PAGE ____ OF ____
DATE 5-20-65

I. HYDROGEN HEATER SYSTEM — SCHEMATIC DIAGRAM

2. HYDROGEN HEATER SYSTEM — TENTATIVE ARRANGEMENT

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DATE 5-20-65