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FINAL REPORT
SELF-CONTAINED GENERATOR FOR SHELTER USE
1 July 1963 to 30 June 1964

15 October 1964

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Department of Army -- OSA
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ABSTRACT

A self-contained generator was designed, assembled, and operated to provide oxygen, water, and electric power in shelters through the decomposition of 90% hydrogen peroxide. The decomposition of hydrogen peroxide in this self-pressurizing unit resulted in complete conversion to oxygen and water at 1300°F and pressures up to 200 psig. A high speed 2 kw turbine, specially designed and manufactured by General Thermodynamics Corp. for this project, was successfully operated in conjunction with a high speed generator. The maximum overall efficiency of the system was 63.4 per cent. For a 100-man shelter, 19.3 lb/hr or 40 gallons per day of 90% hydrogen peroxide will provide the minimum oxygen and water requirement and yield about 0.55 kw (continuous) electrical power or 13.2 kw-hr per day of electrical energy.

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I. INTRODUCTION

The objective of the program was to design, assemble, and operate a self-contained generator unit based on decomposition of concentrated hydrogen peroxide to produce oxygen, potable water, and electric power for use in sealed shelters.

The concept of this multipurpose or self-contained generator is particularly adaptable to closed or sealed shelters in which the ventilation system may be shut down for some reason—to exclude toxic gases and heated air from an adjacent fire, for example. The generator would produce three commodities that are needed in shelters--electric energy, potable water and oxygen for breathing. Such a system could also be useful after the assumed sealed period, when minimum requirements for drinking water must be provided and auxiliary power is desirable, if not essential, throughout the necessary period of occupancy. The generator would eliminate the need for another auxiliary power supply for use when sealed operation is not necessary. The same turbo-generator could be driven by a conventional steam boiler when oxygen can be replaced by ventilation and potable water is more economically available from a well or other source.

II. SUMMARY

A self-contained generator was designed, assembled, and operated to provide oxygen, water, and electric power for use in a shelter through the decomposition of 90% hydrogen peroxide. The feasibility of the operation was established with this test unit. The main results of the study are:

1. The decomposition of 90% hydrogen peroxide was carried out in a self-pressurizing type storage tank-reactor unit, resulting in complete conversion to steam and oxygen at about 1300°F and up to 200 psig pressure.
2. The decomposition catalyst, which is a silver screen coated with cerium oxide, did not show any loss of activity in about 40 hours total operating time.
3. A small 2-kw, high speed turbine prototype was designed and manufactured by General Thermodynamics Corporation of North Wilmington, Massachusetts, on this contract. After detailed development work and numerous tests, the turbine operation was satisfactory for limited time periods. Turbine efficiencies of the order of 85 per cent were determined.

4. A high speed generator, manufactured by Varo Company, Santa Barbara, California, was modified for this application and coupled with the turbine. Generator and transmission efficiencies were about 75 per cent.
5. Measurements of electrical output and analysis of the products were completed at a series of operating conditions. The maximum overall efficiency was 63.4 per cent, which is much higher than expected, and very promising, considering the difficult task of turbine development at this small output.
6. The products consisted of water and oxygen fit for consumption, without catalyst, hydrogen peroxide, or lubricant contamination.
7. For a 100-man shelter, 19.3 lb/hr or 40 gallons/day of 90% hydrogen peroxide will provide the minimum oxygen and water requirement, and also yield about 0.55 kw electrical power or 13.2 kw-hr/day of electrical energy.

Based on these technical data and economical considerations, the development of a shelter prototype unit could be initiated.

III. DESCRIPTION OF THE SHELTER GENERATOR SYSTEM

A. GENERAL INFORMATION

1. Shelter Requirements

The design of a self-contained generator was based on a 100-man shelter. The estimated minimum requirement of oxygen, water, and electric power for such a shelter is presented in Table 1.

Table 1

MINIMUM REQUIREMENT OF OXYGEN, WATER, AND POWER IN SHELTERS

	<u>Per Man</u>	<u>Per 100 Men</u>
Oxygen, lb/day	2.0	200
Water, lb/day	2.5	250
Electric Power, kw-hr/day	0.24	24

These minimum requirements for oxygen, water, and electric power in shelter, are subject to wide variations. The daily requirement for oxygen of 2.0 pounds/man is representative for a low level of physical activity. The daily water requirement

of 2.5 pounds/man may increase by a factor of two or more if the environment is warm. The requirement for electric power may vary from about 10 watts/man for ventilation and low-level lighting to about 50 watts/man if mechanical cooling is also needed. Thus, the electric energy requirement may be from 0.24 to 1.2 kilowatt-hours per day. A system that produced 500 watts of power would provide illumination in a 100-man shelter ventilated by a manually driven blower.

Material Balance of the System

The properties of 90 weight percent hydrogen peroxide are summarized in Table 2.

Table 2

PROPERTIES OF 90 wt-% HYDROGEN PEROXIDE

Specific gravity (68°F)	1.39
Freezing point	+12°F
Weight of 1 gallon	11.6 lb
Heat liberated/lb solution	1106 Btu
Lb O ₂ /lb solution	0.423
Lb H ₂ O/lb solution	0.577
Adiabatic decomposition temperature	1364°F
Partial pressure of oxygen	4.29 psia
Partial pressure of steam	10.40 psia

The adiabatic decomposition temperature given in Table 3 applies to atmospheric pressure (ref. 1). No data are available at elevated pressures.

The decomposition reaction of 90% hydrogen peroxide in an adiabatic reactor produces a mixture of oxygen and steam at a temperature of 1364°F. The decomposition can be conducted under pressure either by a self-pressurizing arrangement that pressurizes the entire supply tank, or by using a liquid feed pump. The first option was selected for our application and a self-pressurizing unit was constructed.

The feed requirements and product quantities are given in Table 3.

Table 3

FEED REQUIREMENT AND PRODUCT QUANTITIES

(1 kw per hour unit)

	Feed	Products	
	90 wt-% H ₂ O ₂	Oxygen	Water
lb/hr	19.3	8.2	11.1
lb/day	463	196	267
gallon/day	39.9	--	32
% of requirement	--	98	107

It should be mentioned here that electrolytically produced hydrogen peroxide was used exclusively throughout our entire experimental work. It was supplied by Food Machinery and Chemical Corporation, Becco Chemical Division. No attempt was made to use hydrogen peroxide produced by organic methods, since trace amounts of organic contaminants would deactivate the catalyst and thus not permit a repeated cold start-up of the unit. This observation was made repeatedly during previous work (ref. 1).

Ninety weight percent hydrogen peroxide was selected for several reasons. The proportion of oxygen and water produced by its decomposition roughly corresponds to the minimum requirements of these materials. The adiabatic decomposition temperature of 98% hydrogen peroxide is 1735°F, which is very close to the upper limit of tolerance of present construction materials, while the decomposition temperature of 1364°F for 90% hydrogen peroxide should not impose serious material problems on the turbine.

The fuel requirement of a 1 kw per hour unit was calculated from the data of the Bureau of Mines (ref. 2), giving theoretical hydrogen peroxide requirements in lb/sec as a function of chamber pressure and H₂O₂ concentration for a 1000 horsepower (HP) turbine expanding isentropically to 1.0 atmosphere. At a chamber pressure of 300 psia (inlet to turbine manifold) the theoretical requirement of 90% hydrogen peroxide is 1.96 lb/sec per 1000 HP. Assuming a turbine efficiency of 70% and a generator efficiency of 70% this will result in an hourly flow for a 1 kw per hour turbine of:

$$\frac{1.96 \text{ (lb/sec x 1000 HP)} \times (3,600 \text{ sec/min})}{745.5 \text{ (kw/1000 HP)} \times 0.7 \times 0.7} = 19.3 \text{ lb/hr-kw (1)}$$

The same calculation for hydrogen peroxide of different concentrations results in the following data:

70 wt-% solution	37.7 lb/hr
80 wt-% solution	25.4 lb/hr
90 wt-% solution	19.3 lb/hr
95 wt-% solution	17.3 lb/hr
100 wt-% solution	15.6 lb/hr

This table indicates that the fuel requirement to drive a one kilowatt unit increases substantially at lower concentrations. At the same time, use of more concentrated hydrogen peroxide only slightly reduces the required fuel storage. Also, the price of hydrogen peroxide increases with its concentration, as indicated below:

70% solution	\$0.308 per lb
90% solution	\$0.615 per lb
98% solution	\$1.00 per lb

These prices are not strictly comparable, since only the first price applies to tank car quantities.

Furthermore, it appears that long-term storage of 90% hydrogen peroxide should result in lower spontaneous decomposition than the storage of a more concentrated solution.

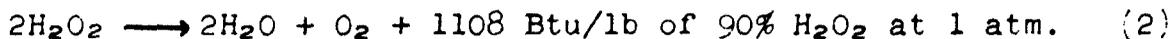
3. System Flow Sheet

The generator system consisted of a hydrogen peroxide storage tank decomposition reactor, self-pressurizing assembly, turbine with accessories and controls, and electric power generator. The flow diagram of the system based on use of hydrogen peroxide is shown in Figure 1.

The concentrated 90% hydrogen peroxide was stored in a 10-gallon 347 stainless steel tank 12 feet above ground level in the test cell. The reservoir was equipped with the usual safety equipment (safety valve, rupture disc, wall temperature indicator), a level indicator, and connections required by the process.

The decomposition reactor was located 1 foot above ground. The line connecting the reactor with the storage tank incorporated a check valve and a micro-regulating valve.

The stored hydrogen peroxide flowed under its hydrostatic head into the reactor where it decomposed according to the equation:



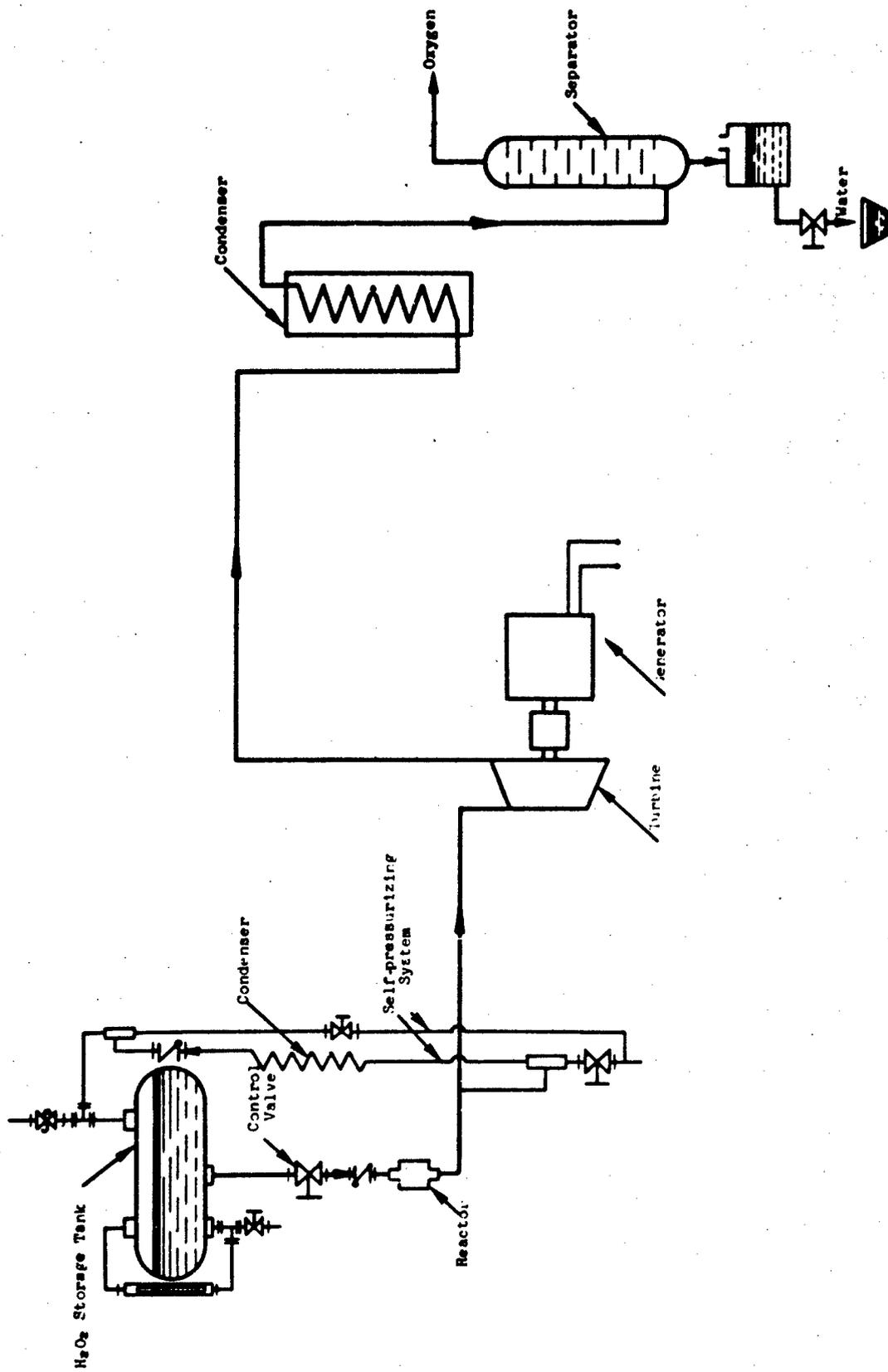


Figure 1. Schematic Flow Diagram of the System.

The exothermic heat effect of the decomposition reaction heated the product stream to an adiabatic decomposition temperature of 1364°F. The decomposition products themselves were used to pressurize the system. The steam in the product stream was condensed in an air cooled condenser, and only the product oxygen was introduced into the storage tank to pressurize it. When the designed operating pressure was reached, the hot and pressurized product stream was then introduced into the high speed turbine. The turbine was directly coupled with a high frequency generator that produced electric energy for use in the sealed shelter.

The expanded exit stream of the turbine was introduced into the product recovery system, where the steam was condensed and separated from the oxygen. The product water was collected, and the oxygen was metered by a rotameter.

4. Storage of Hydrogen Peroxide

Concentrated hydrogen peroxide is insensitive to mechanical shocks according to the manufacturer's information. "Card Gap Tests", "Adiabatic Compression Tests" and "Dynamite Tests" showed its insensitivity (ref. 1). The reaction products of hydrogen peroxide are non-toxic and non-flammable. Experimental results on storage of 90% hydrogen peroxide in 99.5 aluminum drums during shipment around the country show a loss per year ranging from 0.4 to 2.1%, in average 0.9% per year (ref. 3). If the containers are lined with Teflon[®] the decomposition loss per year can be reduced to about 0.1% or even less.

Proper provisions had to be taken in the design and manufacture of the hydrogen peroxide storage tank and feed line to ensure the stability of the stored hydrogen peroxide. All parts exposed to concentrated hydrogen peroxide were manufactured from 347 stainless steel, which shows slight bronzing of the surface but no corrosion.

All stainless steel parts were passivated before use. The passivation procedure consisted of the following steps (ref. 1):

- a. Degreasing with solvent and/or detergent (trichloroethylene).
- b. Flushing with potable water.
- c. Immersion in 70% nitric acid for 4-5 hours at room temperature.
- d. Washing with potable water, flushing with distilled water, drying.
- e. Conditioning with 90% hydrogen peroxide for 3-4 hours.

No excessive decomposition of the stored hydrogen peroxide was noticed, although the hydrogen peroxide tank was connected between experiments to a wet test gas meter. Only on one occasion, where most probably some catalyst particles were carried over with the pressurizing stream into the storage tank, was decomposition observed. The decomposition was brought under control when the system was cleaned and flushed.

In extremely long-term storage of concentrated hydrogen peroxide aluminum or Teflon lining of the containers and lines is advisable.

5. Safety and Handling of Hydrogen Peroxide

The most serious potential hazard in storing and handling solutions containing hydrogen peroxide is the possibility of explosion or detonation. However, a large body of experience is available that delineates the regions of this hazard so that it can effectively be avoided.

The liquid phase system containing only hydrogen peroxide and water at room temperature up to about 96% hydrogen peroxide cannot be detonated by mechanical impact (ref. 3). Hydrogen peroxide in the vapor phase can be exploded if at sufficiently high concentration. At one atmosphere pressure, the explosion limit is 26 mole-% H_2O_2 (40 wt-% H_2O_2), and this drops to about 20-mole-% at 80 psi. However, the relative volatility of hydrogen peroxide above its aqueous solutions is so low that a vapor phase of explosive composition would be formed above concentrated aqueous H_2O_2 solutions only under the most extreme conditions. At atmospheric pressure, with 90 wt-% H_2O_2 solution, an explosive vapor mixture would not be formed until a minimum temperature of 276°F was reached. Much data is available, since the use of hydrogen peroxide mainly for military purposes extends over a period of about 20 years. Explosion hazards do not impose any limitation on this application if the system is designed with appropriate safety measures.

B. DETAILED DESCRIPTION OF THE COMPONENTS OF THE SHELTER GENERATOR SYSTEM

1. Hydrogen Peroxide Storage Tank

The 90% concentrated hydrogen peroxide required for the experiments was shipped in standard 300 lb aluminum drums. The recommended special precautions were followed in handling and transferring the material into the reservoir. A special siphon pump was used to drain the H_2O_2 from the drum into a calibrated glass flask. The cylindrical reservoir was mounted horizontally on top of a steel frame 12 feet above ground level in order to insure continuous gravity feed to the decomposition reactor. The volume of the tank itself was 10 gal; its outside dimensions

were 12 inches O.D. and 32 inches overall length. The material of construction was selected according to the hydrogen peroxide manufacturer's recommendation for high pressure feed tanks: stainless steel 347 was used because of its high structural strength, its corrosion resistance, and its passivity to 90% H_2O_2 . The reservoir was passivated and pressure tested prior to the experiments.

Sudden decomposition of hydrogen peroxide in the tank can occur if the tank is contaminated. This possibility was provided for by a safety valve, set at 320 psig pressure and through a 1 in. diameter rupture disc rupturing at 370 psig pressure. Both relief lines were connected to an outside blowdown tank where hydrogen peroxide could be captured.

The decomposition reactor was fed from the bottom of the tank through a 1/2 in. 347 stainless steel line that incorporated a Whitey micro-control valve for accurate and reproducible regulation of H_2O_2 flow. The reservoir was filled through a separate filling line. Gas pressure could be relieved and adjusted by the vent line and valve. The self-pressurizing line connection entered on the top of the tank. A thermocouple was mounted on the reservoir wall to detect any temperature change. A sight glass type level indicator informed the operator of the amount of stored H_2O_2 . These connections, lines and equipments are schematically indicated on the detailed flow sheet, Figure 2.

2. Decomposition Reactor

The hydrogen peroxide was decomposed in the decomposition reactor, which is shown in Figure 3.

The reactor was made of 347 stainless steel. Its dimensions are 3-1/4 in. overall length and 1-1/4 in. I.D. The arrangement of nickel and cerium oxide coated silver screens is also shown in Figure 3.

The inlet end of the reactor incorporated a check valve and was connected to a shut-off valve. The outlet end directly joined to the pressure and temperature measuring probes and the self-pressurizing 3/8 in. O.D. line before entering the flexible turbine inlet connection. A thermocouple was attached to the wall of the reactor indicating the progress of the decomposition.

3. Self-Pressurizing System

The self-pressurizing system was incorporated into the reservoir and the decomposition systems. A gravity loaded check valve at the reactor inlet directed pressure surges toward the outlet and into the self-pressurizing line if the turbine control valve was closed. The self-pressurizing line between the reactor outlet and the storage tank was connected to an air condenser, a coiled

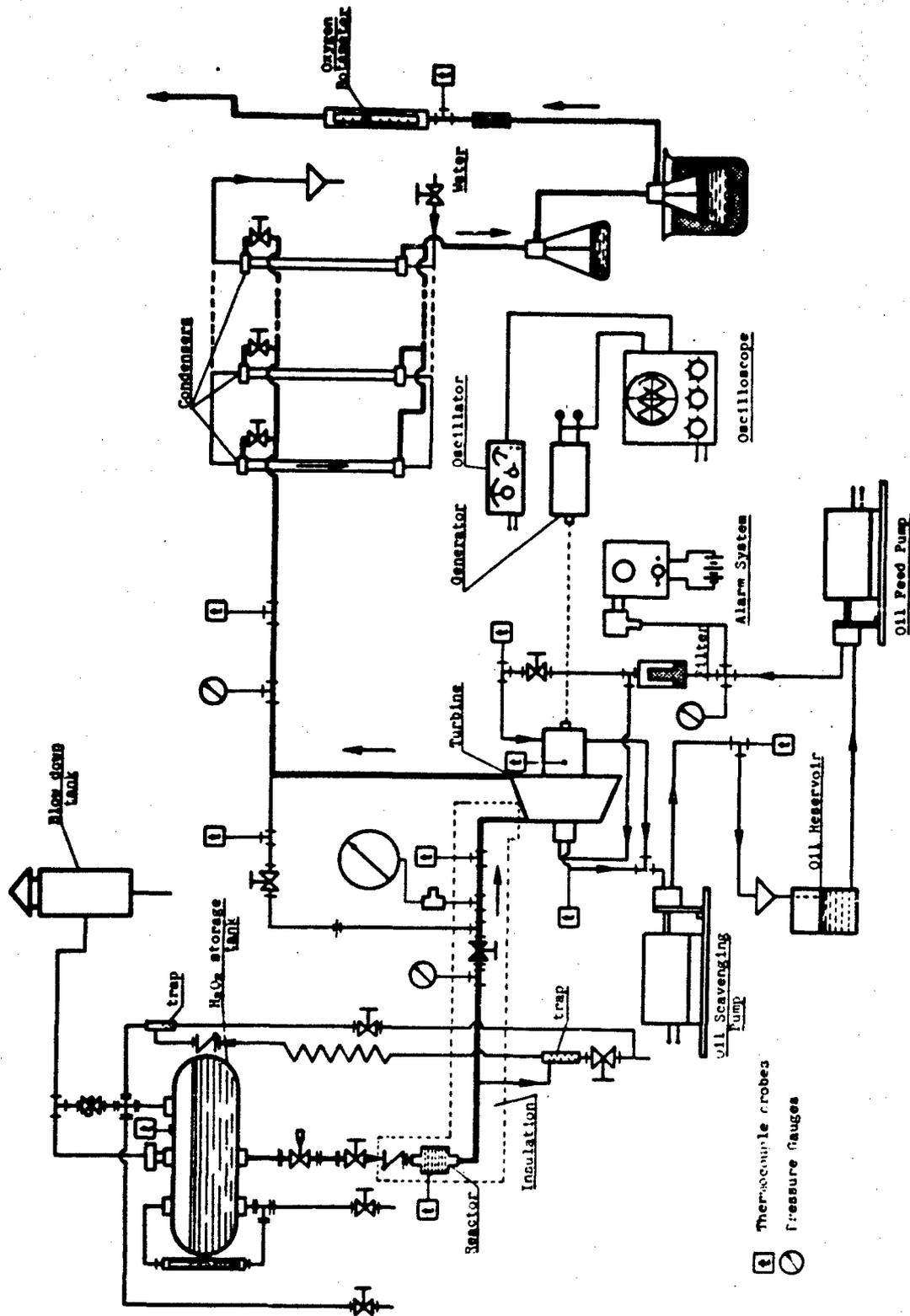


Figure 2. Detailed Flow Diagram of the System.

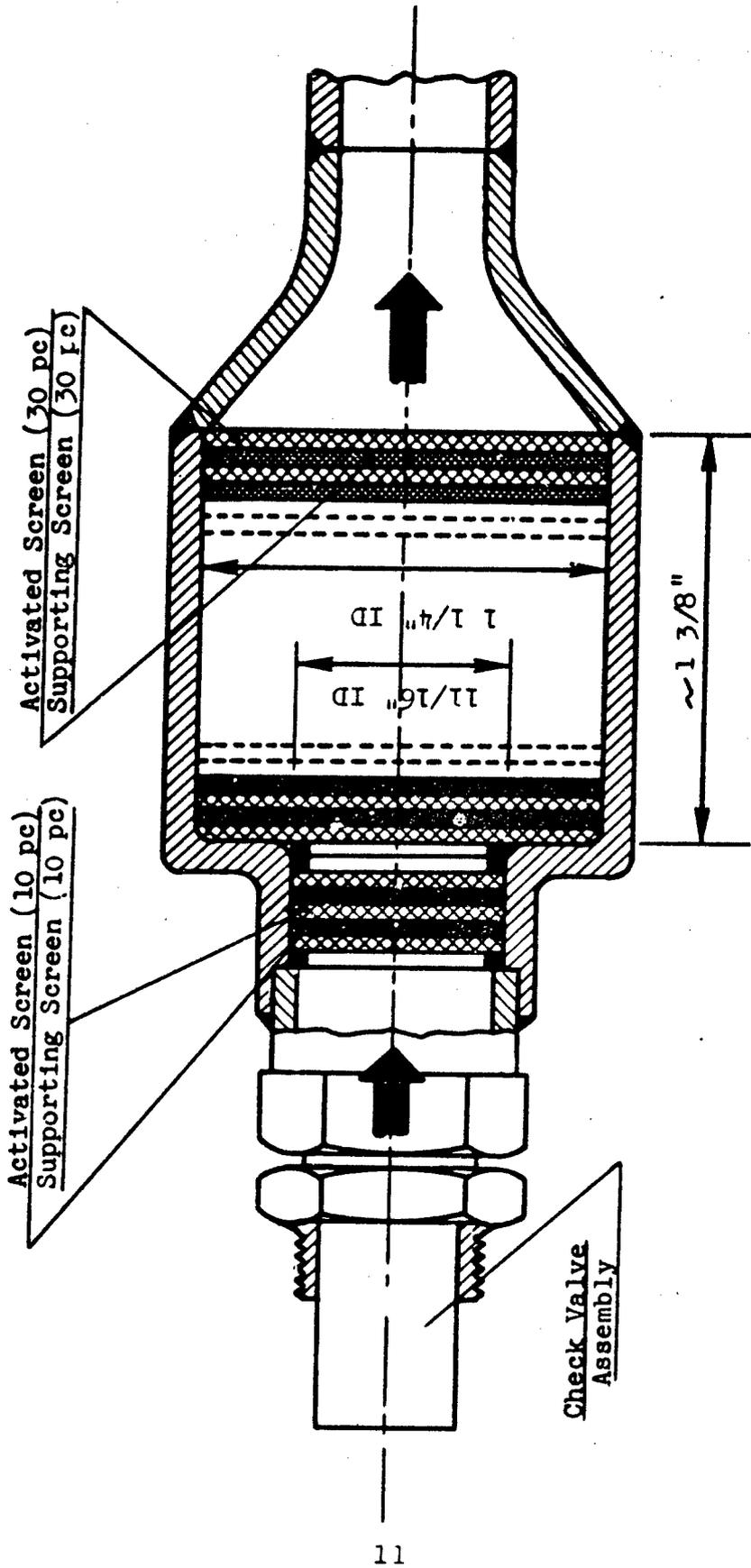


Figure 3. Cross Section of the H₂O₂ Decomposition Reactor.

spiral of 3/8-inch O.D. tubing, and the line passed through two condensate collecting and separating traps and a check valve that prevented reverse flow of oxygen. One of the separators, shown in Figure 2, was placed on the top of the reservoir for trapping any carry-over from the spiral condenser*. Both traps were equipped with a blow-down valve.

4. Turbine

The hot product gases leaving the reactor pass through a flexible metal hose connection and enter the high speed turbine where the energy of the product gases is utilized.

The purpose of this flexible hose (321 stainless steel, 3/8 ID, bellows-type, 8 in. long) is to absorb the vibrations of the turbine, which otherwise would be transferred to the reactor where the resonant effect would be damaging. A special-construction swaged 0.062-inch diameter thermocouple was inserted into the gas stream to measure the turbine inlet temperature.

An intensive survey of turbine manufacturers was carried out before the design and construction of the present unit for this project was ordered from General Thermodynamics Corporation of North Wilmington, Massachusetts. About fifteen turbine manufacturers were contacted. None of them carried a small enough turbine that would satisfy temperature (1350°F) and pressure (300 psia) requirements.

General Thermodynamics Corporation was interested in undertaking the development and construction of the turbine. Originally the unit (Figures 4, 5) was designed as a 3-in. mean diameter overhang type, impulse, two-stage, reverse flow turbine. Its original design parameters were:

inlet temp: 1350°F
outlet temp: 700°F
max rpm: 70,000
max output: 2000 W.
inlet pressure: 300 psig

The turbine shaft was supported in three superprecision ball bearings (Fafnir-2MM-9101 WO). One pair of the bearings carried all the axial loads in addition to the radial components. A third bearing acted as a support and permitted free thermal expansion of the relatively long shaft. Since General Thermodynamics Corporation reserved the right of withholding all but

* Addition of a filter to trap catalyst particles would be advisable at this location, because even minute catalyst contamination of the hydrogen peroxide feed stock would greatly decrease its storability.

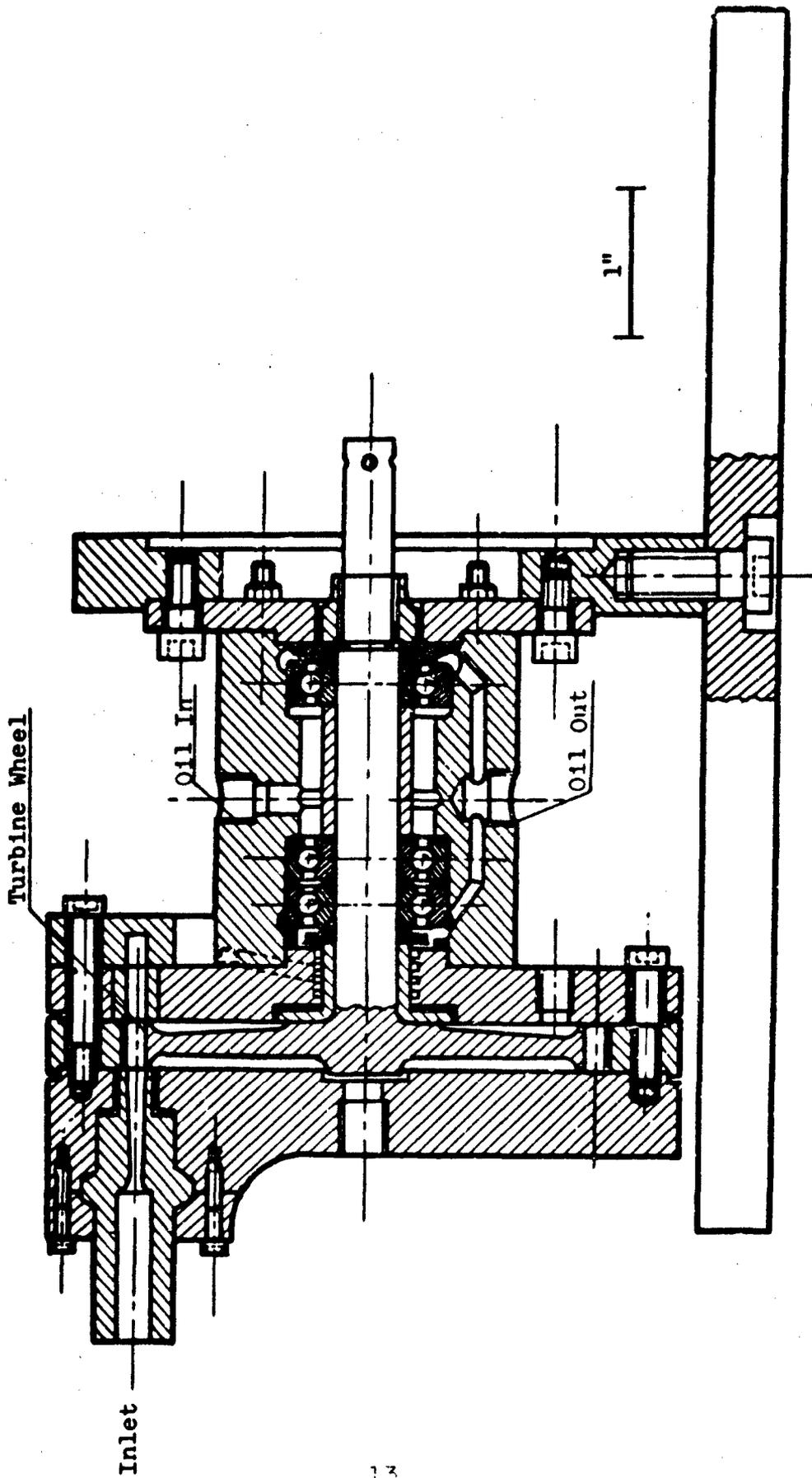


Figure 4. General Layout of Prototype Turbine.

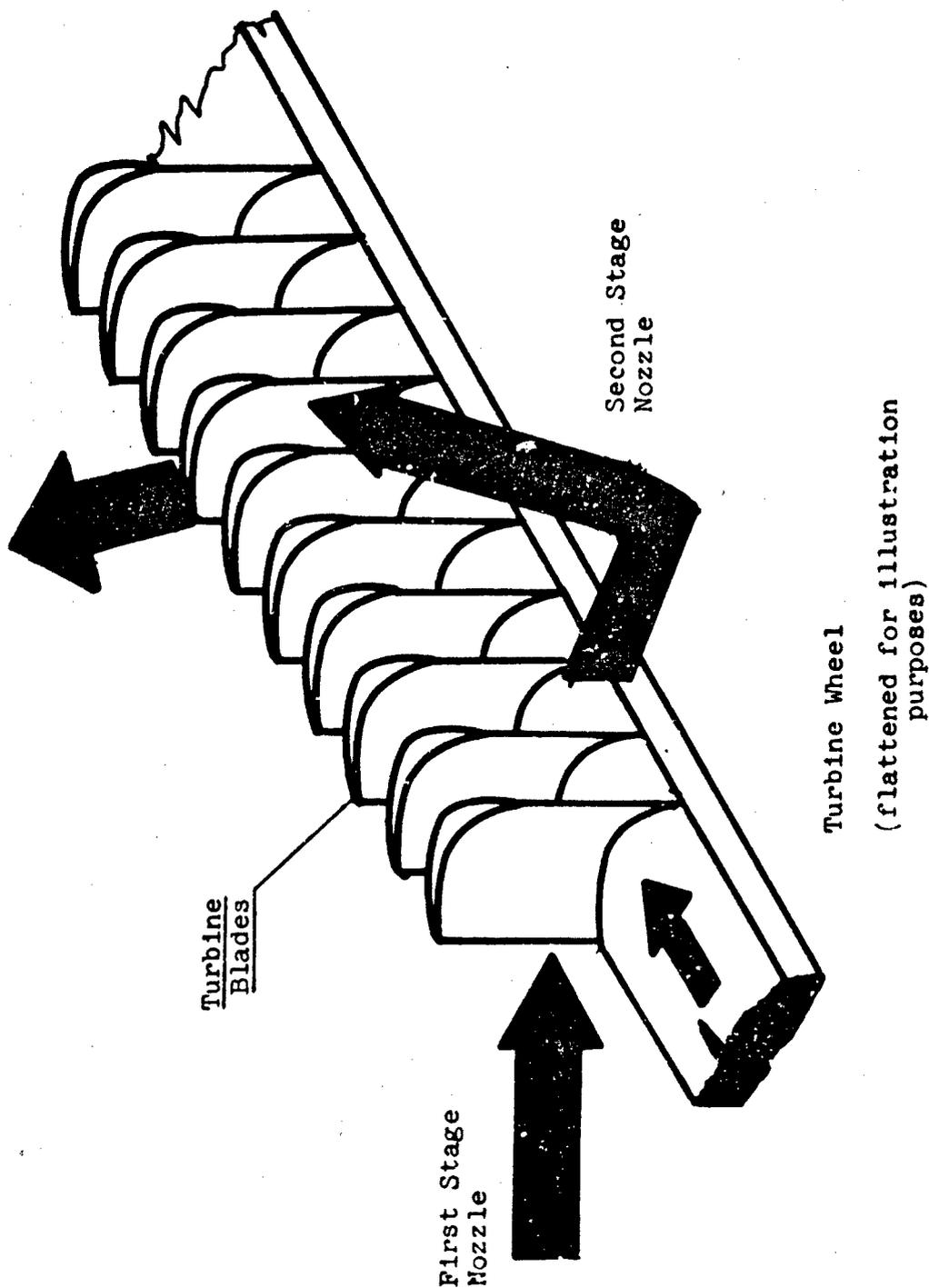


Figure 5. Schematic Diagram of the Flow Path in the Turbine.

the most necessary information, no detailed data on the turbine design calculations are available. The housing was machined of stainless steel. The turbine wheel, which is integral with the shaft, was precision cast of high temperature and corrosion resistant "Waspalloy" metal. The inside of the housing was chromium plated to increase its resistance to the hot oxygen gas and steam.

The bearings were lubricated by Esso TJ-15 turbine oil circulated by a gear pump.

Contamination of the product gases by the lubricating oil was prevented by a four-stage, free-vent labyrinth seal and an oil throw disk.

The turbine was tested for free running with air at the place of manufacture before it was connected to the decomposition system. A high speed electronic stroboscope (General Radio Company Type 1531-A Strobotac) was used during the early part of the tests to determine the speed of the turbine.

During the tests, extensive vibrations of the turbine, were experienced over a wide speed range above 17,000 rpm. These vibrations were probably associated with the natural frequency of transverse motion of the rotating parts. The turbine repeatedly froze up due to labyrinth seizure and front (turbine side) bearing failure. A trial and error procedure customary in the prototype development process was followed to eliminate these difficulties. The manufacturer changed the ball bearing setup to a sleeve bearing. The larger support area of the shaft would have dampened the vibration of the shaft and also would decrease the specific load on the bearings. Though the modified bearing resulted in smoother operation, repeated damage of the bearing occurred at about 22,000 rpm. For all these reasons the original design of the turbine was changed to that shown in Figure 6.

The turbine wheel received an extension shaft, which was supported by an outboard bearing mounted in a housing attached to the outboard turbine wall. An oil throw disk and a labyrinth seal was installed on the new shaft. The lubricating system was expanded by adding an oil scavenging pump, which relieved the bearing housings of excessive lubricating oil.

This straddle support of the turbine wheel resulted in a substantial improvement in the operation of the turbine. A photograph of the turbine-generator unit is shown in Figure 7.

5. Generator

Two ways to utilize the output of the turbine for production of electricity were possible. Since shelter applications would require 115-230 V, 60 cycle AC current, the obvious solution

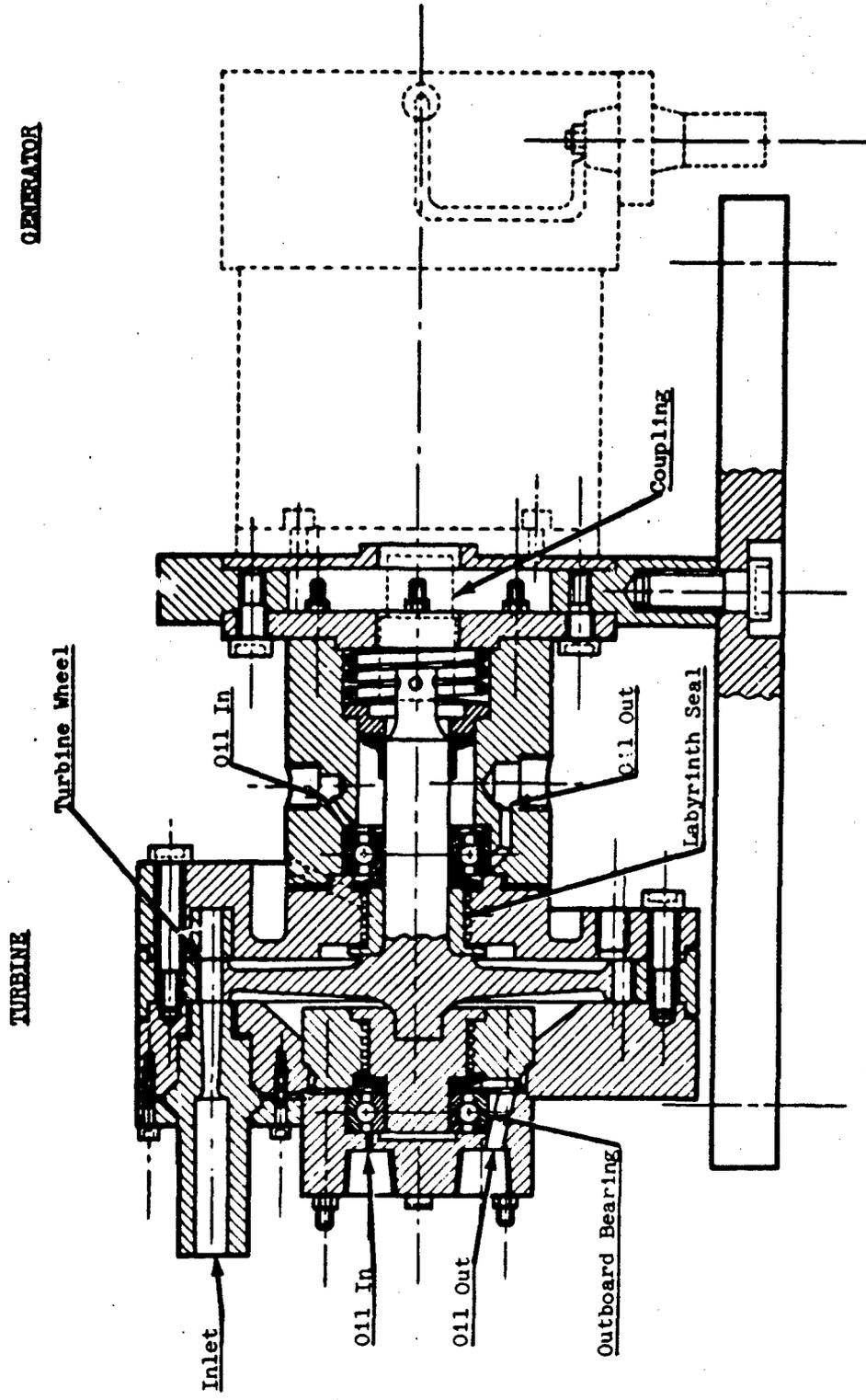


Figure 6. General Layout of the Modified Turbine and Contour of the Generator.

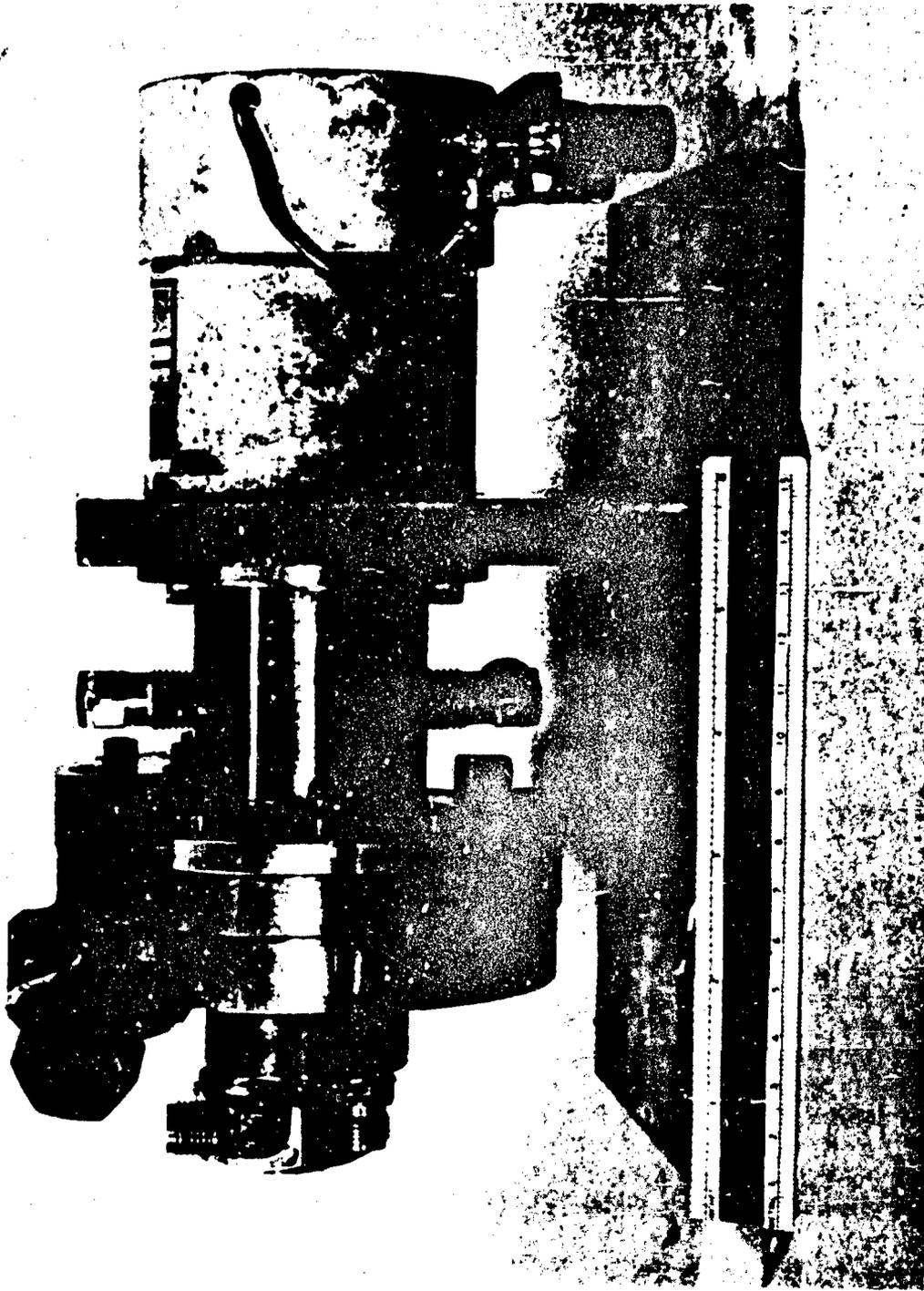


Figure 7. Photograph of Turbine-Generator Unit

would have been a low speed generator with these output characteristics. This type of generator is readily available on the market, but difficulties were encountered in obtaining a gear reducer unit with a 60,000 rpm to 3600 rpm reduction. These units are not only expensive, but introduce additional friction losses. The second solution, which was selected for this project, was a high speed, high frequency generator coupled directly to the output shaft of the turbine. Varo, Inc., of Santa Barbara, California, manufactures this type of generator, which they call a "Flux Switch Inductor Generator", primarily for missile applications. The high frequency output of the generator can be utilized directly for lighting purposes or converted through solid state rectifiers for other applications, for example to supply communication equipment, DC motors, etc.

A schematic-cross section of the generator purchased for this project is shown in Figure 8. The rotor consists of a stack of laminations, completely free of windings, slip rings, brushes or rotating magnets. The stator assembly normally contains four basic poles by incorporating two permanent magnets into the stator lamination. The dotted lines in Figure 8 illustrate a typical flux path through the magnetic circuit of the generator. Change in the angular position of the rotor forces the flux to pass alternately through the rotor to the first set of stator poles and then to the other set (flux switch). The alternating and reversing flux induces a voltage in the generator output windings. The number of revolutions of the motor per second (N) multiplied by the number (P) of salient rotor poles (six in case of Model A19E) yields the frequency f (cps) of the output.

$$f = P \times N \quad (3)$$

Thus, under comparable conditions of speed and for the same number of poles, the flux switch inductor generator will produce twice the output frequency of a wound rotor unit (ref. 4). For example, at 50,000 rpm the frequency is 5000 cps. The high frequency character of the output current greatly increases the phase angle, θ , between current and voltage. Therefore a capacitor correction must be applied to optimize the power factor ($\cos \theta$) in the load circuit. The capacitor was connected in series with the generator. These correcting capacitor values and performance characteristics of the generator are given in Figure 9. The mounting of the generator on the turbine base is shown in Figures 6 and 7.

6. Product Recovery System

The expanded products leaving the turbine passed through a 12 in. long flexible metal hose which eliminated transfer of vibration from and to the turbine. Pressure and temperature readings were taken before the stream entered a bank of five vertical 5/8 in. OD, 30 in. long copper tubing condensers. A

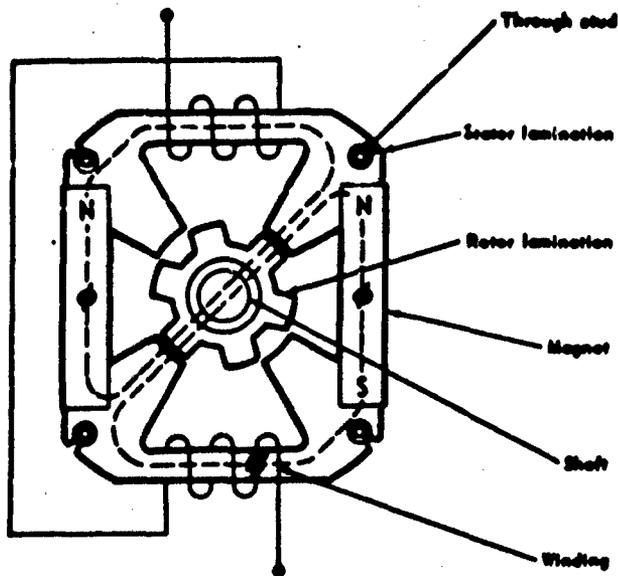


Figure 8 . Flux Switch Inductor Generator.

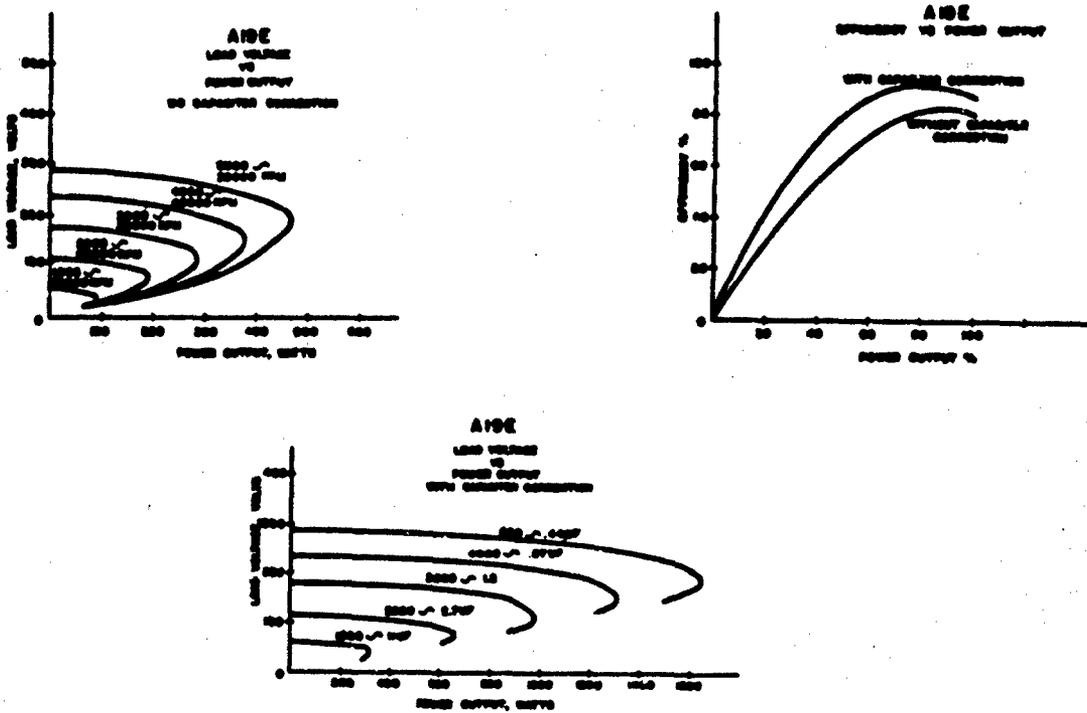


Figure 9 . Typical Performance Curves of VARC A19E Generator.

concentric 5/16 in. OD copper tube carried the cooling water countercurrent to the product stream. Using line water, the products were cooled from approximately 600°F inlet temperature to 100-134°F depending on the turbine load. The cooling water was introduced at a flow rate of about 300 lb/hr or about 36 gallons per hour and its temperature rise was of the order of 60-80°F, depending on the exact flow rates. The condensate water was separated and collected in two Erlenmeyer flasks, while the oxygen stream was measured by a Fischer and Porter Type B6-27-10/27 rotameter.

7. Instrumentation

a. Temperature Measurement

The temperatures required for process evaluation or control were measured by K-type thermocouples and recorded by a Bristol Selectomatic (0-1500°F range, multiple point) temperature recorder. Temperature probes were inserted into the stream similarly to the turbine inlet thermocouple connection shown in Figure 10. The location of the thermocouple probes is noted in Figure 2.

b. Pressure Measurement

The most important process pressure, namely, the turbine inlet pressure, was measured by a 16 in. diameter, 0-300 psig laboratory-type Heuse pressure gauge connected to a protecting snubber. Standard 4 in. diameter gauges were used as shown in Figure 2 to measure other pressure values.

c. Flow Measurement

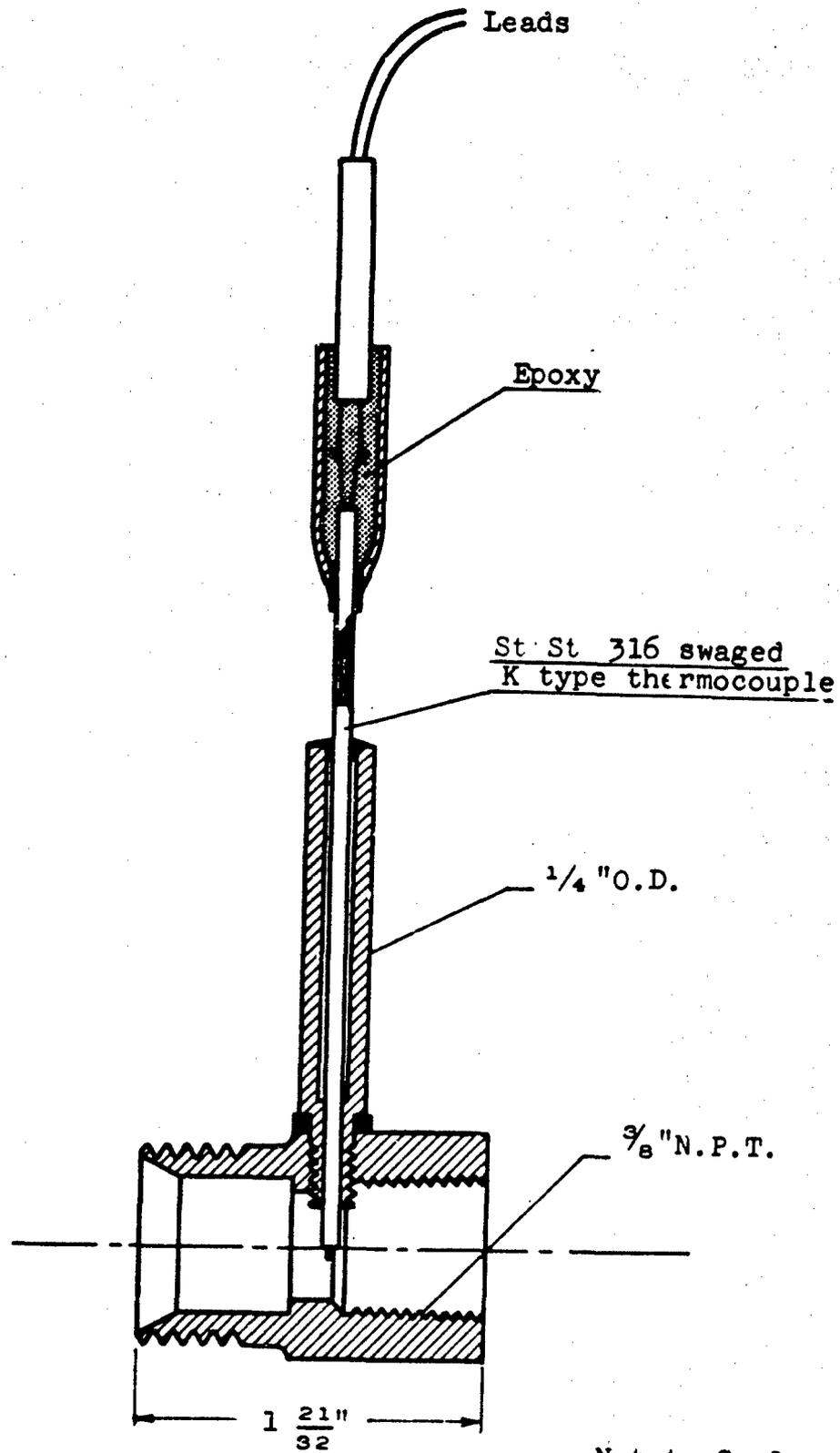
The oxygen production was measured by a Fischer and Porter glass rotameter located at the outlet of the recovery system. The rotameter, Type B627-10/27, and the float (Type SV-T-64) were factory calibrated.

d. Turbine Speed Measurement

The revolution measurement of the direct coupled turbine-generator unit was based on the relation stated earlier (Equ. 3) between the frequency of the generator output, the number of the salient rotor poles, and generator speed.

If N is given in rpm (N') rather than rps, then

$$f = \frac{PN'}{60} \text{ cps} \quad (4)$$



Not to Scale

Figure 10. Thermocouple Probe for Turbine Inlet Temperature Measurement.

In our case, the A19E generator has six salient poles. Therefore,

$$N' = 10f \text{ rpm} \quad (5)$$

The revolution measurement thus was reduced to a frequency measurement, and the latter was completed in two steps with the equipment schematically shown in Figure 11.

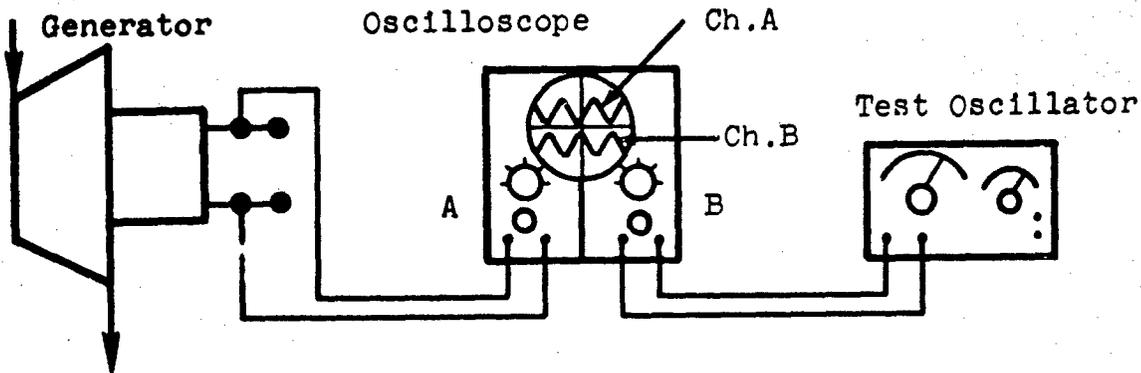


Figure 11. Schematic Diagram of Generator Revolution Measurement Circuit.

The output of the generator was fed to the A channel of a Dual Trace Oscilloscope (Tektronix 545A). Using the same time base, the variable output of a Hewlett-Packard 650-A Test Oscillator was introduced into channel B of the oscilloscope. The output frequency of the oscillator was changed until the number of wave signals matched the number of wave signals produced by the generator. The matching frequency could be readily obtained from the oscillator and converted to revolutions per minute according to equation 5. Figure 12 shows the two matched traces for a 40,500 rpm run.

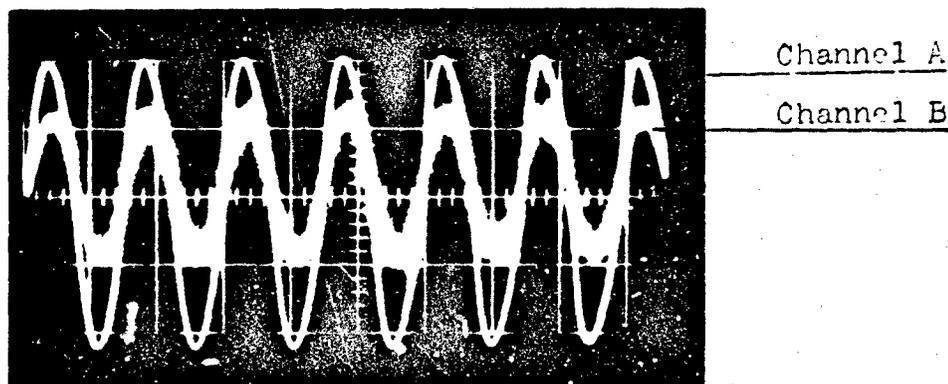


Figure 12. Oscillogram of the Generator and Oscillator Output for Revolution Measurement.

e. Generator Output Measurement

The high frequency of the generator output current caused difficulties in measuring the capacity of the generator. The traditional method of measuring the load by determining the current and the voltage drop across a load resistance would have required expensive high frequency ammeter and thermocouple type voltmeters. Since other methods, such as rectification of the current and measuring the DC wattage, seemed to be complicated, a simpler measuring setup was assembled using readily available instruments as shown in Figure 13. One or more incandescent lamps were used for the load which were connected to the output connections through a variable corrective capacitor. After the generator started to produce electricity, the filament of the incandescent lamp began to glow regardless of the output frequency. The intensity of light was measured with a G.E. Type PR-3 Exposure Meter attached to a 12-3/4 in. x 2-3/8 in. x 7/8 in. light shade. The relationship between light intensity and electrical load was established experimentally for each bulb. Thus, the light intensity readings of the meter could be converted into actual load values.

The calibration of each bulb was made individually using a variable 50 cycle a-c source and a laboratory ammeter and voltmeter.

One of the calibration curves, together with the schematics of the calibration circuitry is shown in Figure 14.

IV. OPERATION AND RESULTS

A. DECOMPOSITION UNIT

In the following the operation of the decomposition unit, providing a hot, pressurized stream for the turbine, is discussed in detail. The decomposition unit consists of the hydrogen peroxide storage tank, decomposition reactor, and self-pressurizing system.

Since the turbine generator unit was designed to operate at elevated pressures and temperatures, the H_2O_2 feed had to be pressurized. The simplest way to achieve pressurization was to use the decomposition products. Figure 15 explains the principle of self-pressurization. Opening the control valve (1) permits H_2O_2 to enter into the reactor due to the hydrostatic pressure head. The fast decomposition produced large volumes of hot gases. Consequently, the pressure increased. When the turbine control valve (2) was closed, the hot gases passed through the condenser and equalized the pressure between the reservoir and the reactor. Since the pressure in the reservoir and that in the exit line of the reactor were always equalized, the hydrostatic pressure of the H_2O_2 column resulted in continuous flow of H_2O_2

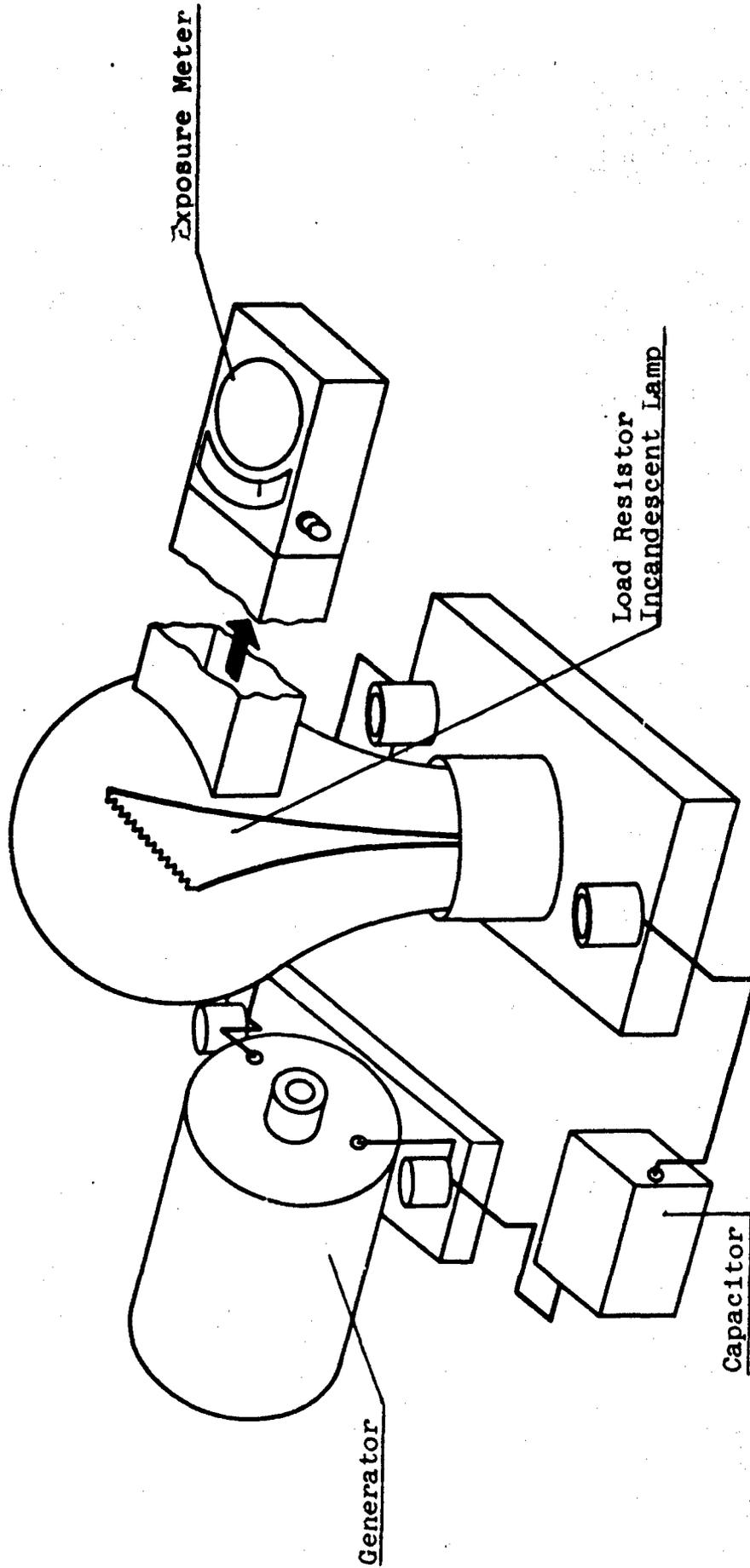


Figure 13. Schematic Diagram of Generator Output Measuring System.

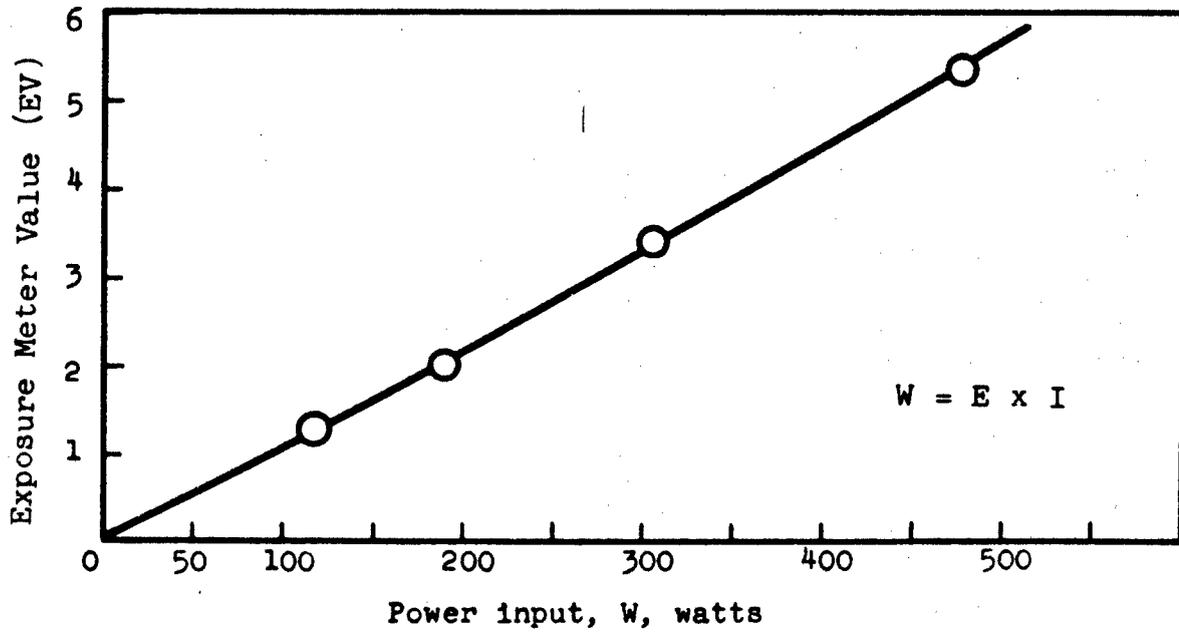
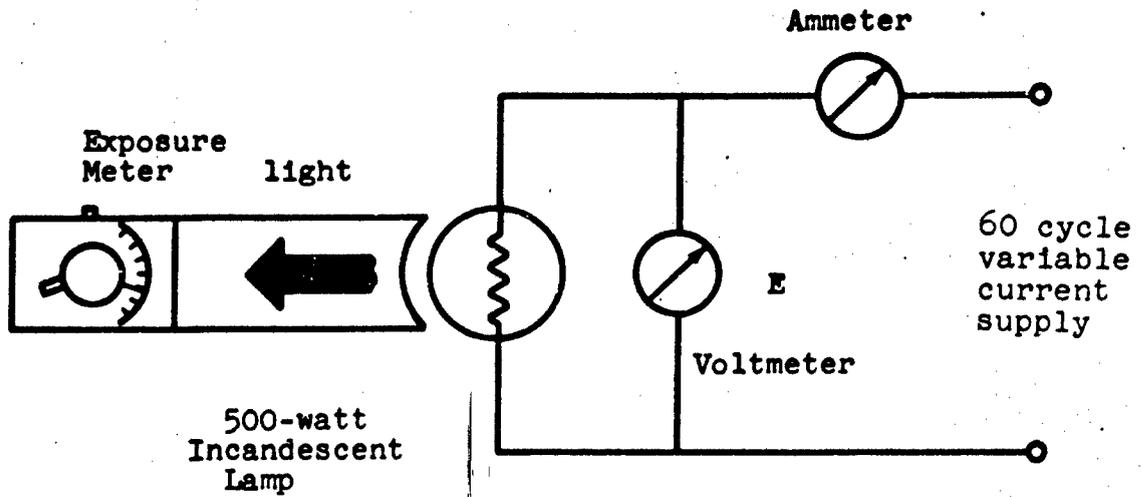


Figure 14. Calibration Curve for the Load Resistor Incandescent Lamp.

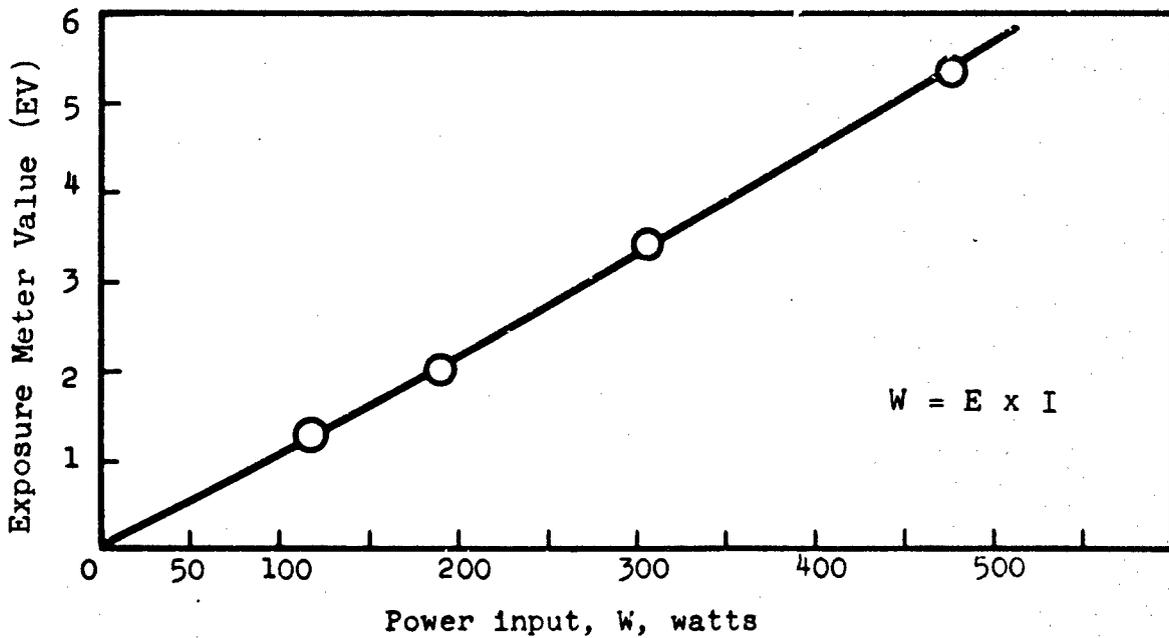
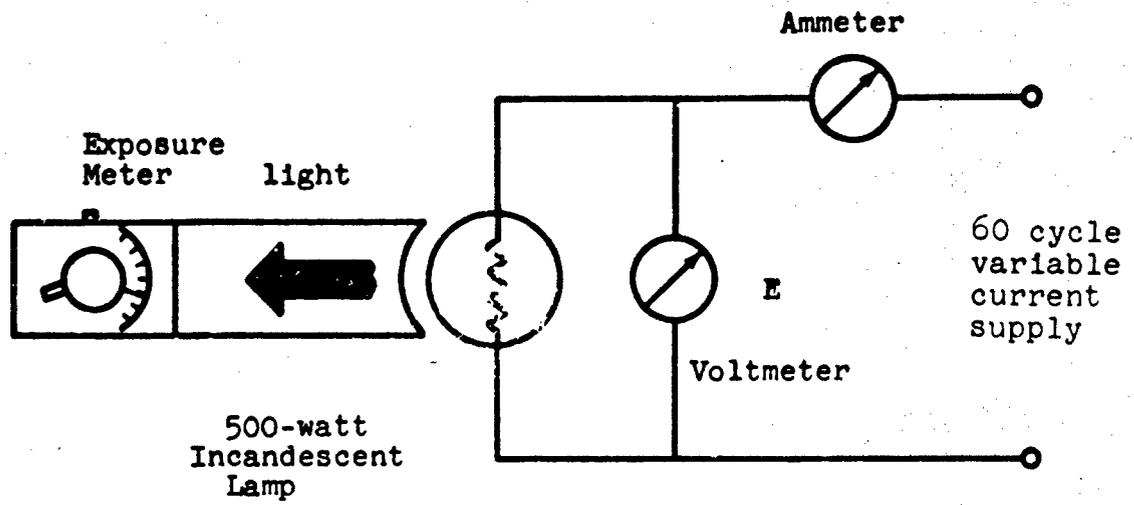


Figure 14. Calibration Curve for the Load Resistor Incandescent Lamp.

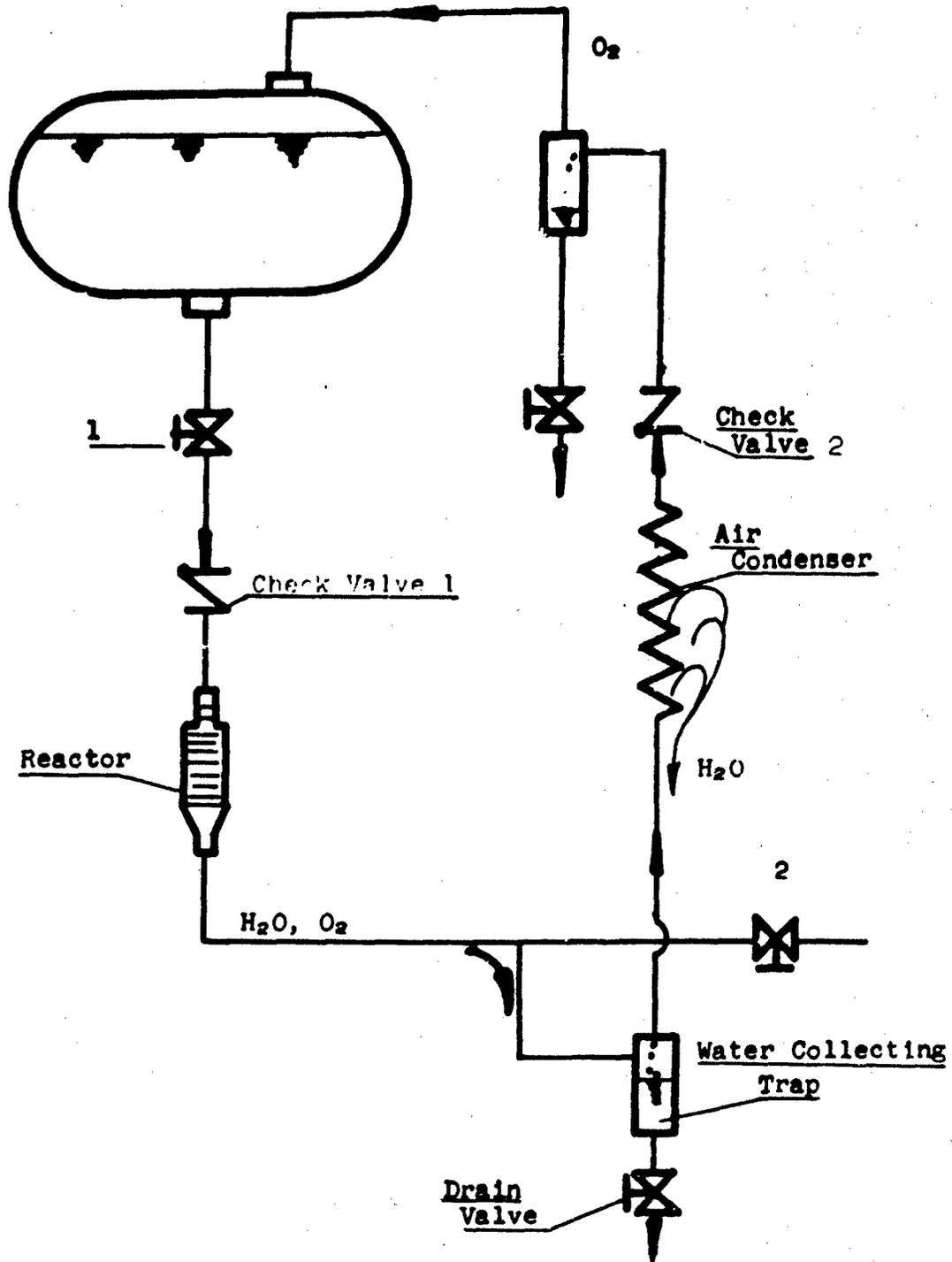


Figure 15. Flow Sheet of the Self Pressurization Process.

to the reactor. Since the product water vapor was separated in the condenser and collected in a trap, only oxygen returned to the reservoir. The temperature of the reservoir remained constant during this operation. In careful operation, avoiding sudden pressure surges, the condenser and the trap prevented return of the condensate or stream into the reservoir, and the dilution of the pressurized hydrogen peroxide.

The pressure build-up during the self-pressurization process up to 300 psig for a 10-gal reservoir 90% filled with H_2O_2 solution, is plotted in Figure 16. It can be noted that about 50 minutes were needed to reach 300 psig pressure.

If instantaneous turbine-start-up is required, the reservoir can be pressurized by bottled oxygen. During turbine operation, a part of the decomposition products was used to maintain the pressure in the reservoir by replacing the consumed liquid H_2O_2 .

The turbine generator can be started at a pressure as low as 60 psig with a production of about 200 watts of electrical energy. Thus the minimum start-up time for limited power generation is about 25 minutes.

In an emergency, water and oxygen can be obtained instantaneously using the bypass line of the turbine, without pressurizing the storage tank and without production of electrical energy.

The decomposition of hydrogen peroxide was carried out in a small reactor containing an active catalyst package. This package consisted of thirty 1-1/4 in. diameter silver screen discs, separated from each other and supported by thirty 1-1/4 in. diameter nickel screens. Superimposed on this package were ten 11/16 in. diameter silver screens, packed alternately with ten 11/16 in. diameter nickel screens. The silver screen was 20 mesh, prepared from 0.011 in. diameter wire. The nickel screen was 20 mesh, from 0.012 in. diameter wire. The silver screen was activated by repeated coating with cerium oxide. This coating did not seem to be sensitive to shock or vibration. The small 11/16 in. package on the top of the catalyst bed acted as a starter catalyst. The entering concentrated hydrogen peroxide heated up this smaller diameter portion of the catalyst bed faster, thus raising the temperature of decomposition rapidly and providing a high rate of decomposition.

Experiments were carried out to check the degree of conversion at different flow rates up to 40 lb per hour maximum flow rate. The products did not show any traces of unconverted hydrogen peroxide under normal operating conditions. The decomposition started instantaneously in the cold reactor on introduction of the feed solution. The flow rate had to be increased gradually in the first 5 minutes to permit the reactor

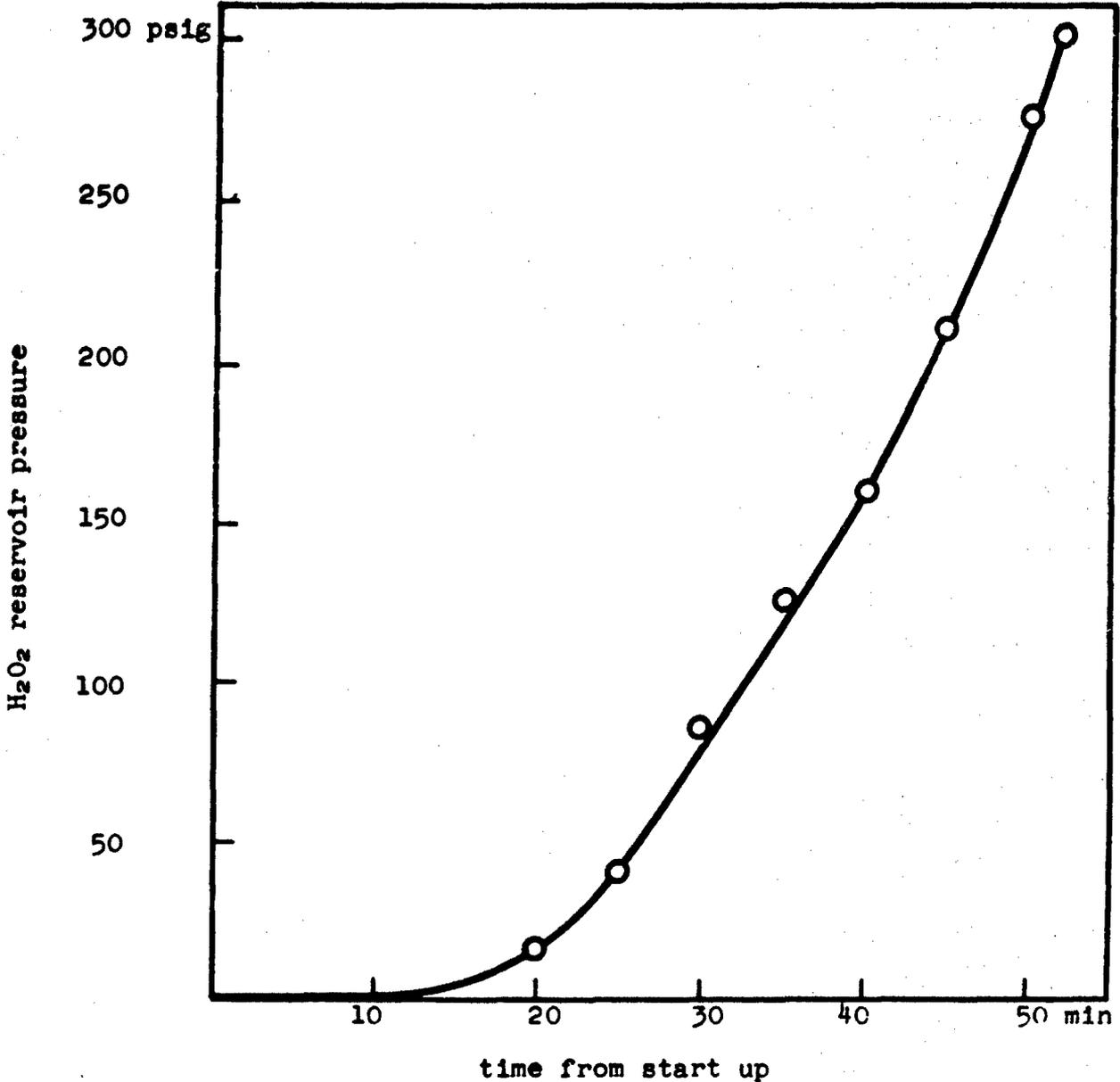


Figure 16. Pressure Build-up in H₂O₂ Reservoir during the Self-Pressurizing Process. Reservoir was initially filled to 90% of its volume.

to reach the adiabatic decomposition temperature. An introduction of the feed at flow rates of 10-15 lb per hour at start-up resulted in incomplete conversion, however.

The hydrogen peroxide content of the condensed water was checked repeatedly during operation. Potassium permanganate (0.01N) indicated no hydrogen peroxide content; samples of condensate (200 ml) were colored by a single drop of this reagent to the same extent as blanks of distilled water.

The calculated adiabatic decomposition temperature of hydrogen peroxide is 1364°F. The experimentally determined temperature of the decomposition products measured at the inlet of the turbine was about 1320°F. This minor difference was caused most probably by the heat losses of the reactor and connecting tubing. The temperature inside the reactor was not measured, but a thermocouple was attached to the outside of the reactor beneath its thermal insulation. A constant reading on this thermocouple indicated trouble-free operation of the entire decomposition system.

The catalyst bed was operated for about 40 hours under varying loads with numerous start-ups and shut-downs. No change in activity of the catalyst was noticed. (This should not be true if hydrogen peroxide produced by organic methods is used. Minute trace contaminations with organic materials should lead to a fast loss of activity of the catalyst bed).

In summary, the operation of the decomposition unit was very satisfactory and gave a highly uniform stream of hydrogen peroxide-free products.

B. ELECTRIC POWER GENERATION

In the final testing of the turbine and generator efficiency, five experiments were carried out. During these runs the operating conditions were kept constant, the pressures and temperatures were recorded, the oxygen production was measured, the turbine speed was measured, and the electric output determined. The experimental data are summarized in Table 4.

From the data on oxygen production, the flow rate of hydrogen peroxide was calculated. In this calculation the water vapor content and the temperature of the exit oxygen stream had to be considered. For the further evaluation of the data, the Mollier diagram of 90% hydrogen peroxide as given by the U. S. Naval Air Rocket Test Station (Lake Denmark, Dover, N. J.) was used. A portion of this Mollier diagram, showing the inlet and outlet conditions of experimental run No. 1 and 3, is reproduced in Figure 17. From the enthalpy values given in this diagram, the theoretical equivalent electric energy can be calculated (1 kw-hr = 3,412.76 Btu).

EXPERIMENTAL DATA ON THE OPERATION OF THE SYSTEM

Run No.	H ₂ Ca Flow rate lb/hr	Steam and Oxygen Inlet Conditions Temp. °F	Steam and Oxygen Outlet Conditions Temp. °F	Pressure psig	Products Water lb/hr	Oxygen lb/hr	Cooling Requirement Btu/lb feed	Btu/hr
1	30.29	1225	710	80	17.48	12.81	839	25,400
2	20.60	1300	710	94	17.08	12.52	839	24,830
3	31.10	1305	720	100	17.95	13.15	843	26,210
4	34.11	1300	730	106	19.68	14.43	846	28,870
5	33.15	1300	740	120	19.13	14.02	850	28,180

Run No.	Turbine Speed rpm	Running Time Hours	Energy Electric Output watt-hr	Power watts
1	23,000	0.50	283	565
2	30,200	0.45	380	845
3	32,500	0.62	542	874
4	33,500	0.35	328	937
5	55,000	0.48	461	960

Cooling water was introduced at a flow rate of approximately 300 lb/hr and its temperature increased by about 60-80°F.

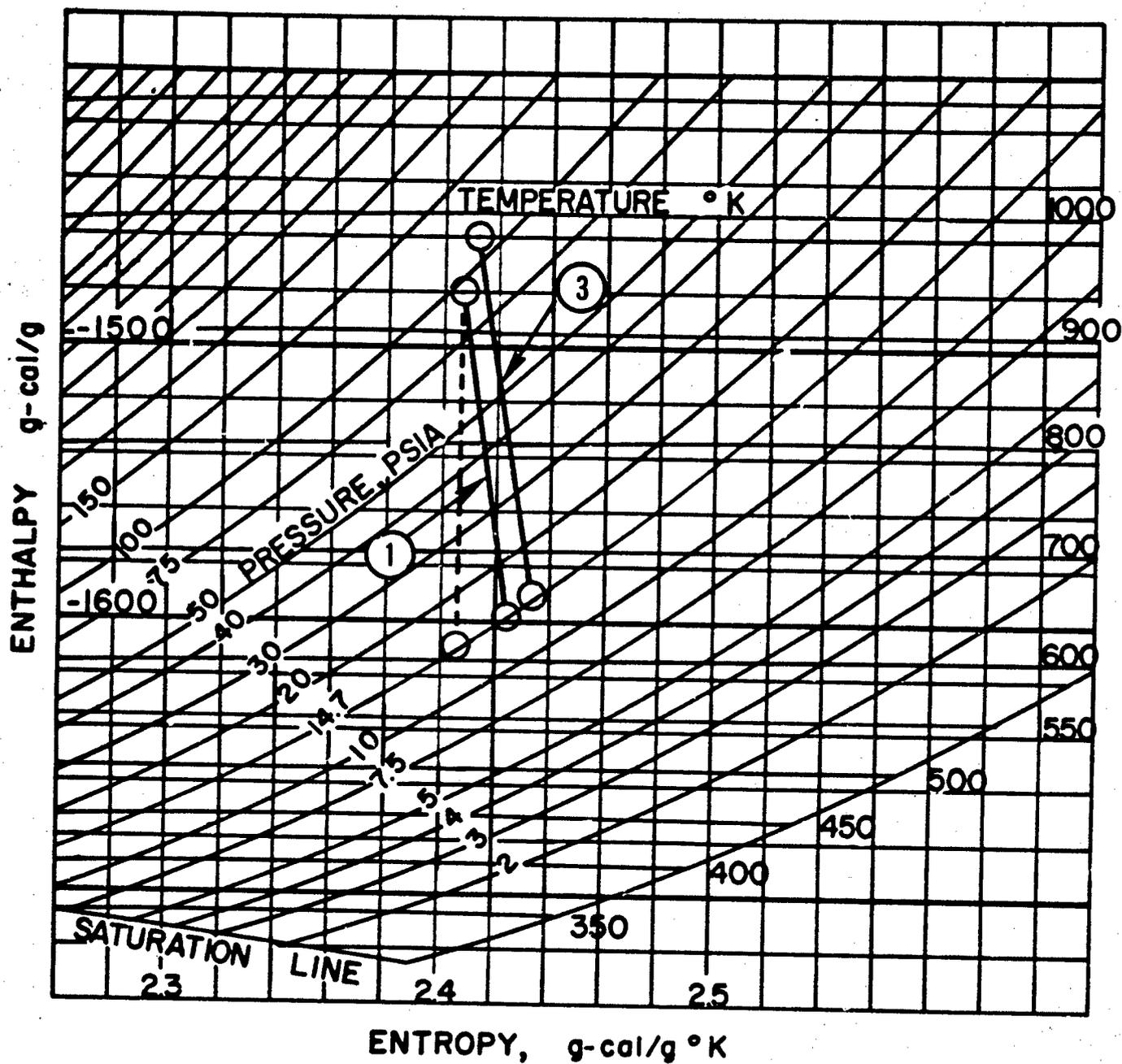


Figure 17. Enthalpy-Entropy Diagram of Decomposition Products of 90 wt-% H₂O₂

The given pressure in the enthalpy-entropy diagram is the total pressure of the decomposition products. As can be seen from this figure, the product mixture is highly superheated. There is room for further improvement of the efficiency by increasing the inlet pressure and temperature or by reducing the outlet pressure and temperature. These considerations could be applied in the design, development, and testing of follow-up turbine models to obtain higher turbine efficiency. Operation under reduced pressure on the exit side of the turbine does not seem promising in this application because of operating complications.

To evaluate the efficiency of the system the following efficiencies were defined:

Decomposition thermal efficiency, η_d , is similar to the combustion efficiency of a gas engine, and gives the ratio of actual enthalpy change to the theoretical enthalpy change:

$$\eta_d = \frac{H_{in} - H^{\circ}}{H_{in}^{th} - H^{\circ}} = \frac{H_{in} - H^{\circ}}{\Delta H_{react.}} \quad (6)$$

where H_{in} is the enthalpy of the inlet stream of the turbine
 H_{in}^{th} is the theoretical enthalpy of the inlet stream of the turbine
 H° is the enthalpy of the fuel at 77°F
 ΔH_{react} is the reaction enthalpy

Expansion or turbine efficiency, η_t , is the ratio of the actual enthalpy change and the isentropic (adiabatic) enthalpy change between the turbine inlet and outlet:

$$\eta_t = \frac{H_{in} - H_{out}}{H_{in} - H_{out}^{isent.}} \quad (7)$$

Conversion efficiency, η_e , accounts for the losses of the generator and transmission and is given by the ratio of electric output to the actual enthalpy change of the turbine:

$$\eta_e = \frac{W}{H_{in} - H_{out}} \quad (8)$$

where W is the electrical energy produced expressed in Btu.

The overall or system efficiency, η_s , can be defined as the product of these three efficiencies:

$$\eta_s = \eta_d \times \eta_t \times \eta_e = \frac{W}{\Delta H_{\text{react.}}} \times \frac{H_{\text{in}} - H^{\circ}}{H_{\text{in}} - H_{\text{out}}^{\text{isentr}}} \quad (9)$$

This relation compares the electric energy produced by the system with the energy produced by a system operating with 100% decomposition, turbine, and conversion efficiency, respectively. The values used in these calculations are given in Table 5.

Table 5
ENTHALPY VALUES OF DECOMPOSED HYDROGEN PEROXIDE

Btu/lb; 90% solution

Exp. No.	H°	$H_{\text{in}}^{\text{th}}$	H_{in}	H_{out}	$H_{\text{out}}^{\text{isentr}}$	$\frac{W}{\text{Btu/lb}}$
1	-2556	-1448	-1480	-1595	-1612	63.7
2	-2557	-1449	-1463	-1595	-1610	97.4
3	-2557	-1449	-1460	-1593	-1608	95.9
4	-2557	-1449	-1463	-1590	-1615	93.7
5	-2557	-1449	-1463	-1587	-1617	98.9

The calculated efficiencies for specific fuel consumptions are given in Table 6.

Table 6
EFFICIENCIES AND SPECIFIC FUEL CONSUMPTION OF THE TURBINE-GENERATOR

Exp. No.	Flow Rate lb/hr	η_d	η_t	η_c	η_s	Spec. Consumption lb/kw-hr
1	30.29	0.971	0.871	0.554	0.469	33.6
2	29.60	0.987	0.898	0.738	0.654	35.0
3	31.10	0.990	0.899	0.721	0.642	35.6
4	34.11	0.987	0.836	0.738	0.609	36.4
5	33.15	0.987	0.805	0.798	0.634	34.5

As can be seen from the earlier Mollier diagram (Figure 17) the turbine operates very nearly isentropically. The efficiency of the turbine could be further increased by full isentropic operation and by reducing the outlet pressure. Since the latter is determined by the back pressure of the condensing and product separation system, and since the measured pressure did not exceed 2 psig, little or no change can be made.

A substantial increase in production of electrical energy could be achieved by operating the turbine at higher inlet pressures. Although the enthalpy of the inlet stream decreases slightly at higher pressures, the enthalpy of the turbine exit stream can be increased substantially. Assuming an average efficiency of 70 per cent, the quantity of 90% hydrogen peroxide required for producing 1 kw-hr is:

<u>Pressure</u> <u>psia</u>	<u>Temp.</u> <u>°F</u>	<u>Pressure</u> <u>psia</u>	<u>Temp.</u> <u>°F</u>	<u>ΔH</u> <u>Btu/lb</u>	<u>Specific Consumption</u> <u>lb/kw hr</u> <u>(70% efficiency)</u>
100	1304	14.7	755	127	38.3
200	1304	14.7	602	158	30.9
300	1304	14.7	503	175	27.9

In this calculation, the same order of deviation from isentropic operation was considered as was shown by the experimental runs. This was indicated in Figure 17 by the deviation of the line representing the expansion from vertical.

The results of these runs show that the overall efficiency of the turbine-generator system increases with the speed, but only minor gains in efficiency can be achieved by operating the turbine above 30,000 rpm. The engine efficiency obtained 60-65%, more than satisfactory. Efficiencies of the order of 80% are obtained only for large well-designed turbines and reciprocating engines. Small units of inferior design show efficiencies down to 30 per cent. The high efficiency of our turbine-generator system indicates very good design and careful manufacture.

V. EVALUATION OF RESULTS

The experimental results of the self-contained shelter generator system indicate that a 100-man shelter can be supplied with the minimum oxygen and water requirement using about 19.3 lb/hr or 39.9 gallons per day of 90% hydrogen peroxide solution. The system also provides electric power for the shelter. If the hydrogen peroxide decomposition system is operating in the 195-210 g pressure range, 35.4 lb of hydrogen peroxide is required to produce 1 kw-hr of electrical energy. The system supplying the minimum oxygen and water requirement at a flow rate of 19.3 lb per hour will provide about 550 watts of power.

ADVANTAGES OF THE SYSTEM

Oxygen and Water Supply

The system supplies both oxygen and water to a sealed shelter in quantities that correspond closely to the minimum requirement.

2. Independence from Outside Air Supply

The unit can be operated for extended periods without any access to oxygen or air. No fumes to contaminate the air of the shelter are produced. The products of decomposition are pure oxygen and water.

3. Reliability, Stand-By Period

A simple turbine-generator system is more reliable than any internal combustion engine. After initial installation and test, the stand-by capability of the unit is practically indefinite. A minimum number of inspections of the system, besides checks on hydrogen peroxide concentration, are envisioned to check reliability during extended periods of storage in shelters.

4. Long-Term Storage

The decomposition rate of 90% hydrogen peroxide can be kept well below one per cent per year. The decomposition of hydrogen peroxide produces oxygen and water only, which will dilute slightly the stored hydrogen peroxide over the years. No sludge, gum, or deposit formation occurs such as may be encountered with other fuels and lead to operating difficulties after extended storage.

5. Availability of High Temperature Heat

The unit produces high temperature steam and oxygen, which is available at the turbine outlet at approximately 700°F. The heat content can be utilized in other shelter units for cooling, air conditioning, or decontaminating the air in the shelter area.

6. Transportability

The entire unit consisting of the decomposition reactor, self-pressurizing system, turbine-generator assembly, pumps and controls, can be mounted on an easily transportable base. The tank for the storage of hydrogen peroxide can be connected to the base-mounted unit, but should not be mounted on the base itself. Thus, the generator unit can be made easily movable.

7. Electric Power Storage

Except for generators driven by internal combustion engines, which cannot be placed into sealed shelters without access to air and disposal of combustion products, the only feasible way to store electrical energy is in the form of batteries. We estimate that a cadmium-nickel battery weighing about 1015 lb or a lead-acid battery weighing about 660 lb would supply the same energy (13.2 kw-hr) in a day. If secondary batteries were used they have to be kept charged for the entire stand-by period.

the operation of the hydrogen peroxide driven generator can be extended by storing more than a 24-hour supply (40 gallons) of hydrogen peroxide.

DISADVANTAGES OF THE SYSTEM

Development Work Required

The state-of-art is not sufficiently advanced to permit the use of shelf items in assembling the generator prototype. Further development work must be carried out to test each component of the unit and to find the best and most economical way for assembling and operating such a unit.

Contamination Danger

The design of the unit must eliminate entirely the possibility of contacting the stored hydrogen peroxide with the decomposition catalyst.

Construction Materials

Precautions must be taken to prevent the contamination of the hydrogen peroxide storage tank and the lines leading to the decomposition reactor. Stainless steel and aluminum should be used as construction materials and all parts of the system connected with concentrated hydrogen peroxide must be deactivated by pretreatment. Although such pretreatment is carried out in the storage, delivery, and use of hydrogen peroxide on a routine basis and does not represent any new problem, it will add to the cost of installation.

Heat Load

If the available high temperature heat is not used, it will add to the heat load of the shelter area. The heat load of a unit producing one kilowatt hour electrical energy is about 30,000 Btu/hr.

FUTURE POSSIBILITIES

The turbine developed on this contract requires further testing and perhaps further development work, to achieve trouble-free, long-life operation.

Based on the present work and on some preliminary cost figures obtained from the manufacturers of the hydrogen peroxide decomposition unit and storage tank and from the turbine manufacturer the cost of a compact shelter prototype unit in units of one hundred can be estimated to be about \$4,500. The cost of hydrogen peroxide could decrease substantially owing to increased competition, especially if hydrogen peroxide manufactured by organic methods can be utilized.

D. USE OF SECONDARY FUEL

No experimental work was done on the use of a secondary fuel for generating electric power.

A secondary fuel would be used after a sealed period during which the turbine generator is operated on pure hydrogen peroxide feed. When the shelter is not sealed, oxygen can be supplied to the shelter area from the atmosphere. The system can then be switched over to operate on a secondary fuel, thus cutting substantially the consumption of stored hydrogen peroxide.

Use of a secondary fuel such as alcohol or hydrocarbon would require substantial modifications of the unit. The main new components would be (1) a secondary fuel storage tank, (2) a secondary fuel feeding device (pump), (3) a combustion chamber that could be combined with the decomposition reactor, and (4) a water recirculation system.

Since the temperature of the combustion products will exceed the maximum temperature of the turbine, part of the product water must be introduced in a mixing chamber ahead of the turbine and be recirculated. The fuel requirement and product quantities for a unit operating on pure hydrogen peroxide and on hydrogen peroxide and ethylalcohol, respectively are as follows:

	<u>H₂O₂ Unit</u>	<u>H₂O₂ and Alcohol Unit</u>
Feed:		
90% H ₂ O ₂ lb/hr	19.3	11.1
92% EtOH lb/hr	-	2.4
Total fuel	19.3	13.5
Products:		
Oxygen lb/hr	8.2	-
Water lb/hr	11.1	9.2
Carbon dioxide lb/hr	-	4.3

The results of our work indicate that such a turbine generator system will produce about 600-650 watts of power. As can be seen from these data, the requirement for stored fuel is reduced by the use of secondary fuel by about 30%, but the secondary fuel must be stored separately and the system loses much of its simplicity. An economic evaluation of both systems, of their installation cost, and of added operating complications based on further experimental evidence and data, could determine whether such a scheme is required and practiced.

VI. REFERENCES

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