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The Design and Development of a Zero-G Vapor Liquid Separator for Use in Cryogenic Fluid Power Systems

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PESCO PRODUCTS, a division of the Borg-Warner Corporation, has carried out studies of cryogenic liquid zero-G separators for cryogenic storage tanks. The first study specifi-cations were, typically:

1. Light weight.
2. No external power source.
3. Extreme high separation efficiencies under all vapor-liquid conditions.
4. Pressure drop: 2 psi maximum for design conditions.
5. Service life: 150 hours, or more.

Very little prior art existed for this zero-G separation problem. Possible methods were:

Static separation.
Vortex separation.
Induced G-field.

Efficiency and pressure drop considerations indicated the use of an induced G-field. (Figure 1 V/L separator pattern). This review traces the theory and development of an induced G-field concept in the following steps:

I. Introduction
II. Analytical Design
III. Cryogenic and Non-Cryogenic Test Plans
IV. Non-cryogenic Simulation
Description of Development Test Units
Evaluation of Test Data
V. Flight Unit Design

Vapor to Liquid Separation Pattern as shown in Figure 1.

ANALYTICAL DESIGN

CALCULATED DROPLET TRAJECTORIES FOR RADIAL INFLOW SEPARATOR. As a design aid, droplet trajectories for the radial inflow portion of the separator have been calculated. The radial inflow portion carries

ABSTRACT

During long coast periods of zero-gravity, storage vessels for the cryogenic liquids proposed for use in some power transmission systems undergo random distribution of the liquid and vapor phases therein. Thus, when heat flow into the vessel causes the vessel pressure to build-up requiring venting to maintain a safe value, the likelihood of venting the valuable liquid phase, as well as the vapor, results. To preclude this eventuality, various devices for separating the liquid and vapor phases and venting just the vapor have been studied and carried into the experimentation stages.

This report presents the data obtained from the analysis, design and development testing of a specific, dynamic type vapor-liquid separator intended for use in a hydrogen storage tank.

Testing completed and reported on herein was non-cryogenic. Model laws of similarity for two-phase operation in the non-cryogenic media were used for determining non-cryogenic test conditions simulating the intended cryogenic application.

Extrapolated cryogenic performance is presented herein as is also the proposed methods of testing in the cryogenic media.

logarithmic spiral, backward-leaning blades. The effect of blade angle has been studied through calculations for 25°, 50°, 75° log spirals. Two rotational speeds, 955 rpm and 2,860 rpm, have been studied. For separators with axial inlet depths of 3 inches and 6 inches, design flow conditions of 38 psi and 30 cubic feet per second of hydrogen vapor have been calculated. Some typical trajectories for droplet sizes of 0.1 and .01 inch are shown. Those trajectories which meet a blade surface between the 6 inch and 4 inch radial position are considered to be separated. Those droplet trajectories which pass a blade surface must be separated in the mixed flow portion of the separator which follows the radial inflow portion as in the X_1 design.

These trajectory calculations show the advantage of the larger blade angles for the radial inflow separator. Estimates of separator efficiency for a fixed droplet size may be made from these trajectories; for such estimates, the separator rotational speed is determined by matching the load imposed by the liquid inlet quality with the turbine characteristic. See Figure 2.

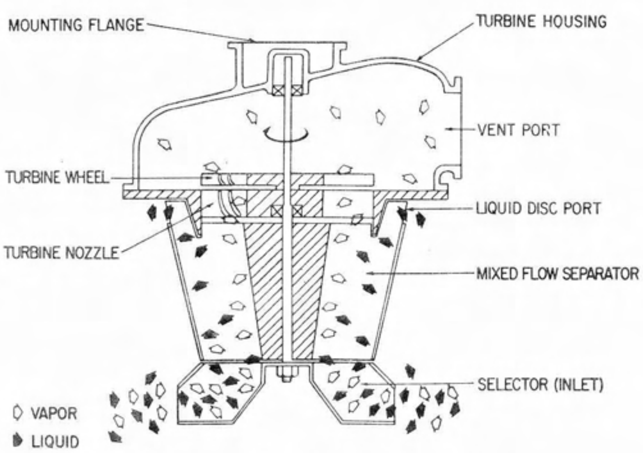


Fig. 1 - V/L separation pattern

CALCULATED TURBINE POWER AND SEPARATOR LOAD CHARACTERISTICS. To determine separator operating speed, typical power-speed characteristics for the turbine must be matched with load-speed characteristics. This is conveniently done on a plot of power per unit mass of vapor flow versus speed. The separator load is essentially determined by the angular momentum at which the separated liquid is rejected. If the vapor mass flow rate is held constant the load is determined by the inlet liquid quality. Lines of constant load are then lines of constant inlet liquid quality on the accompanying load speed diagram. Turbine characteristics have been superimposed for turbines of 50% and 35% efficiency, allowing for a pressure drop of 1 psi across the turbine. The intersection of the turbine characteristic and the load lines determines the speed at which the turbine-separator combination will operate.

These calculations have assumed a constant total pressure drop across the turbine-separator combination of 2 psi, with the further assumption that the separator pressure drop is constant at 1 psi. The flow losses in the separator will not, in fact, remain constant with speed but will increase at the higher rpm. This will result in lower no-load turbine speeds than predicted by this calculation. See Figure 3.

NON-CRYOGENIC AND CRYOGENIC TESTING

PERRY CRYOGENIC LABORATORY

Location:	Perry, Ohio
Staff:	Experienced cryogenic engineers and technicians.
Facilities:	7000 gallon dewar)

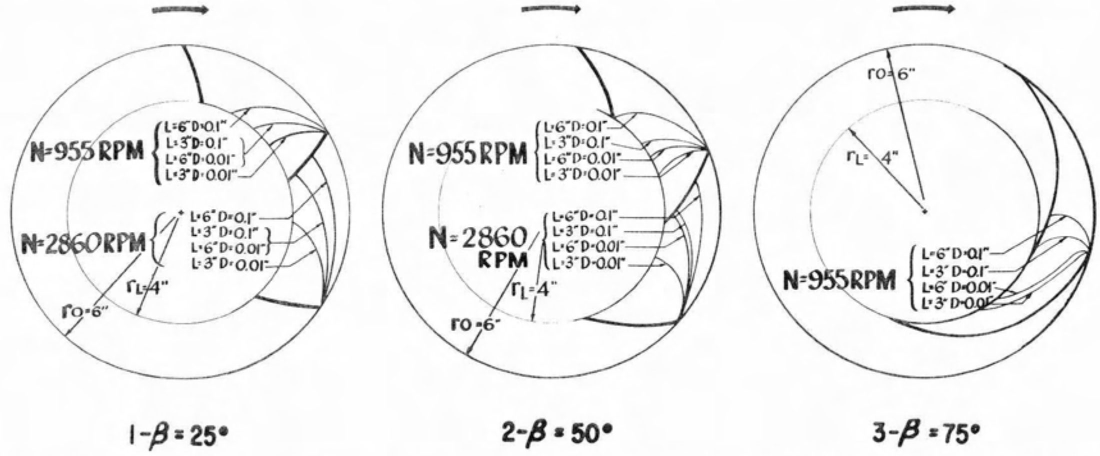


Fig. 2 - Calculated droplet trajectories for radial inflow separator, H_2 @ 38 psia, Q_V = 30 ft 3/sec

1000 gallon dewar) Hydrogen
77 gallon dewar)
Remote instrumentation

Figure 4 shows the non-cryogenic separator test set up (partial diagram).

Figure 5 shows the over-all non-cryogenic test schematic.

SIGNIFICANT FEATURES:

Mixing Tank - Spray ring can be raised, lowered and tilted to alter spray pattern.

Flow rates to 120 gpm water and 2700 cfm air.

View ports for direct observation of separator and turbine while operating.

Drive System (Hydraulic)

Speed range 0 - 8000 rpm

Torquemeter

Speed Pickup

Serves as hydraulic load for turbine tests, as well as a motor.

In operation, the rig permits individual measurement of amount of liquid separated by the selector and mixed-flow separator.

Cryogenic Testing has Serious Limitations:

1. Run time is limited to about 4 minutes.
2. Direct visual observation is limited and difficult.
3. Flow conditions within the unit cannot be measured or observed.
4. Only one operating condition can be run per test.
5. Set-up time is long.
6. Testing is expensive relative to data obtainable.

Non-Cryogenic Test Unit was Designed with the Following Objectives:

1. Hydrodynamically identical with the cryogenic unit.
2. Utilizes common materials such as carton steel and aluminum to expedite fabrication and modification.
3. Separator and selector are individual assemblies to facilitate experimental changes with minimum cost and time.
4. Turbine housing provides for direct observation of flow conditions within the unit.
5. Instrumentation is readily accessible.
6. Unit may be driven by turbine or hydraulic motor, depending on test requirements.

Cryogenic Test Rigs for V/L Separator are shown in Figure 6. These rigs permit

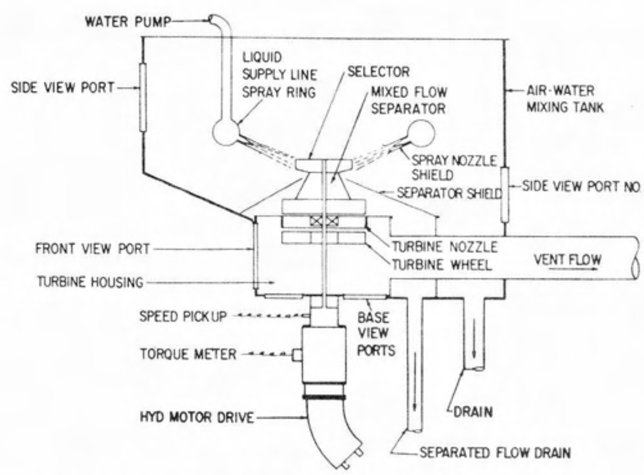


Fig. 4 - Non-cryogenic separator test set up

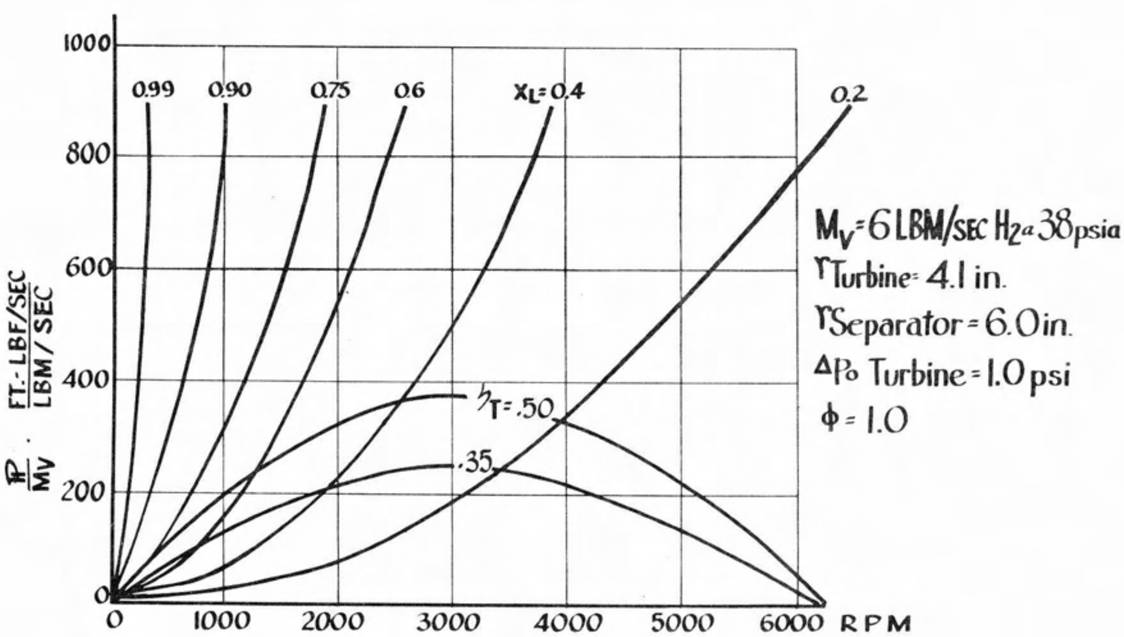


Fig. 3 - Calculated turbine power and separator load characteristics

testing at higher quality than the non-cryogenic rigs.

Cryogenic Testing Allows Evaluation of Two Aspects of Design:

1. Mechanical Details
   - Structural
   - Materials
   - Bearings
2. Over-all Performance
   - Pressure drop
   - Discharge quality
   - Flow rate
   - Speed

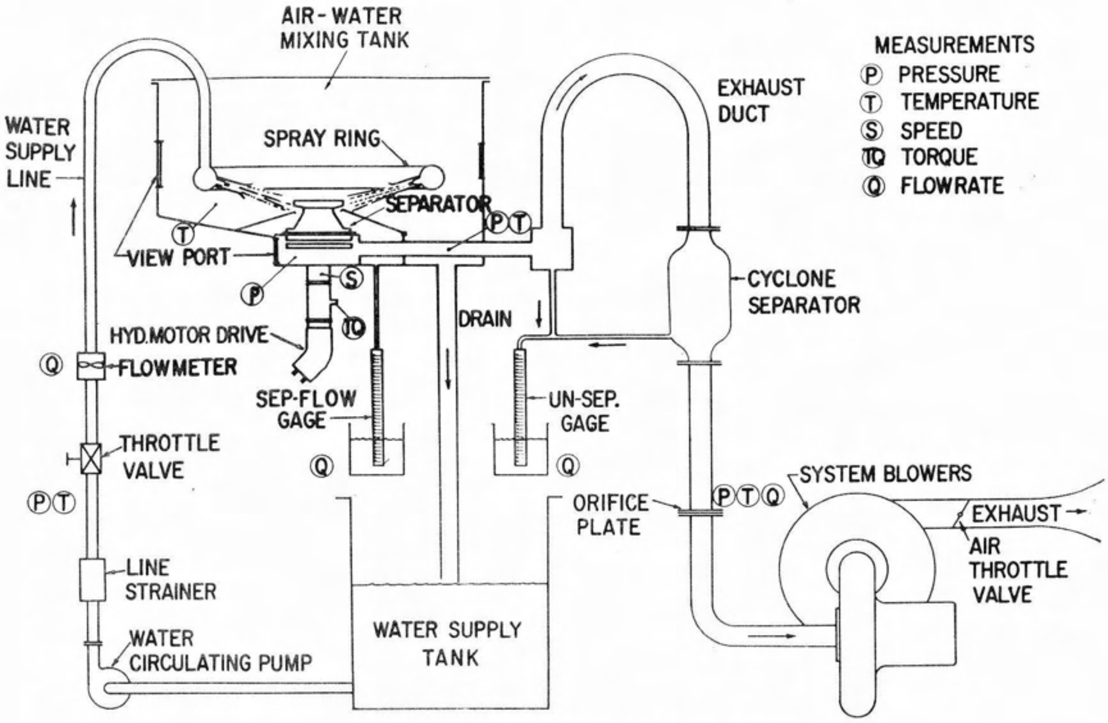


Fig. 5 - Non-cryogenic test schematic

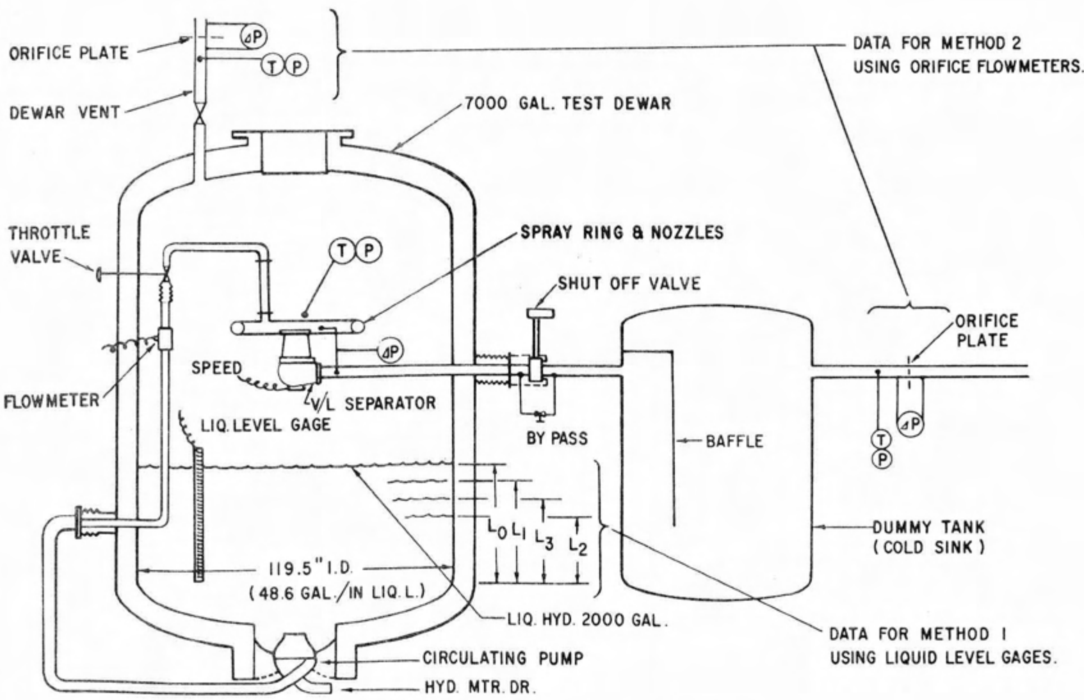


Fig. 6 - Cryogenic test schematic

TYPE OF TESTS

1. Torque Calibration:

Purpose: To determine friction torque of separator.

Test: Speed - 900 to 3000 RPM with hydraulic motor drive. No air and water through flow.

Data: Speed and torque.

2. Air Flow Test:

Purpose: To determine (a) Air distribution inside turbine housing information for turbine design. (b) Separator air pressure drop. (c) Torque HP requirements.

Test: Speed - 900 to 3000 RPM with hydraulic motor drive. Flow - 20, 30, 45 CFS air. No water.

Data: Speed, torque, separator ΔP, air temperature, orifice ΔP, total and velocity pressure plus velocity angles inside turbine housing.

3. Static Water Flow:

Purpose: To determine liquid through flow with venting air with separator non-operational.

Test: Flow - 30 CFS air; Constant 100 GPM, 20 PSI at spray nozzles.

Data: Orifice ΔP, air temperature, separated liquid flow, unseparated liquid flow, circulating pump flow and head.

4. Air-Water Separation Test:

Purpose: To determine separation performance and HP requirement of the unit.

Test: Airflow - 30 CFS. Water flow - 100 GPM @ 20 PSIG. Speed - 900 to 3000 RPM with hydraulic motor drive.

Data: Speed, torque, inlet flow, separator ΔP, ΔP orifice plate, pump head, separated and unseparated liquid flows, air and water temperatures.

5. Turbine Test No. 1.

Purpose: Friction torque measurement without separator at zero airflow.

Test: Speed - 900 to 6000 RPM with hydraulic motor drive.

Data: Speed, torque.

6. Turbine Test No. 2.

Purpose: To determine turbine performance without separator.

Test: Speed - 900 to 6000 RPM with hydraulic motor drive.

Data: Speed, torque, orifice ΔP, air temps.

7. Turbine Test No. 3.

Purpose: To determine friction torque of a turbine-separator combination at zero flow.

Test: Speed - 900 to 4500 RPM with hydraulic motor drive.

Data: Speed torque.

8. Turbine Test No. 4.

Purpose: To determine turbine performance with separator.

Test: Airflow rate - 20, 30, 45 CFS. Speed - To maximum speed with hydraulic motor drive.

Data: Orifice ΔP, speed, torque, air temperature, separator ΔP.

9. Turbine Test No. 5.

Purpose: To determine maximum or no load speed with separator.

Test: Airflow 5, 10, 15, 20, 25, 30, 35, 40, 45 CFS torquemeter and hydraulic motor drive disconnected.

Data: Airflow rate, speed, separator ΔP, air temps.

10. Turbine Test No. 6.

Purpose: To determine separation performance in air-water flow.

Test: Air flow 30 CFS, water flow - 100 GPM @ 20 PSIG. No hydraulic motor drive or speed controls.

Data: Air and water flow rates, maximum separator speed, unseparated liquid flow, water and air temperatures, separator ΔP.

NON-CRYOGENIC TEST SIMULATION. (See Figures 7 through 12).

NON-CRYOGENIC MODEL TESTS. Hydrogen liquid vapor flow has been simulated with an air-water flow for separator model tests. For these tests full-scale separator models have been used. A full-scale model which is run at prototype rotational speeds with the same volume flow rate as the prototype will produce the same droplet

THE CONDITIONS:

$$\omega M = \omega P$$
$$Q\,M = Q\,P$$
$$\left[\frac{D_{DROPLET}\ \rho_{LIQ}}{\rho_{VAP}}\right]_M = \left[\frac{D_{DROPLET}\ \rho_{LIQ}}{\rho_{VAP}}\right]_P$$

WILL GIVE SAME DROPLET TRAJECTORIES IN FULL-SCALE MODEL AND PROTOTYPE SEPARATORS

FOR AIR-WATER @ ATMOSPHERIC COND : $\frac{\rho L}{\rho V} = 840$

FOR SAT. H_2 @ 38 psia : $\frac{\rho L}{\rho V} = 21$,

$$\left[D_{DROPLET}\right]_M = \frac{1}{40}\left[D_{DROPLET}\right]_P$$

Fig. 7 - Non-cryogenic model tests

trajectories in the air-water model as in the hydrogen prototype, for water droplets which are approximately 1/40 times the diameter of the prototype hydrogen droplets. Through such non-cryogenic simulation tests much useful development information can be obtained. For example, some indication of the slip between the rejected liquid droplets and the rotating separator blades as the droplets are discharged can be obtained; measurements of the separator flow loss can be made with vapor flow and with vapor liquid mixtures, to support analytical estimates; observations of vapor discharge angle, which will effect turbine performance, can be made. Measurements of over-all separator performance for the air-water system can be interpreted in terms of equivalent prototype performance. (See Figure 7).

NON-CRYOGENIC TEST DATA - SEPARATOR ONLY. For the non-cryogenic tests the separator was installed so that it could be motor driven. From this installation, torque-speed curves at constant load can be obtained. Both the X_1 and several configurations of the X_4 unit were tested in this manner. The results at design flow rate (30 cubic feet per second) are shown for an inlet liquid quality of 70-85%. These results show that the X_1 unit requires a lower driving torque to accomplish separation than the X_4 unit designs. The data shown was taken at inlet liquid (water) qualities in the 70-85% range. The hydrogen equivalent qualities for these torque curves is 70-85% when the data is plotted on a torque per unit mass flow of vapor basis.

During these motor-driven separator tests, separation efficiency was also measured. These measurements showed that the X_1 unit has higher separation efficiencies than the X_4 designs at all speeds tested. The results show the X_1 unit separation efficiency cirtually constant with speed, and above 99%. These tests were also run at water-liquid qualities of 70-85%. For separation efficiency simulation purposes these water-liquid qualities correspond to hydrogen equivalent liquid qualities of 12-20%. (See Figure 10).

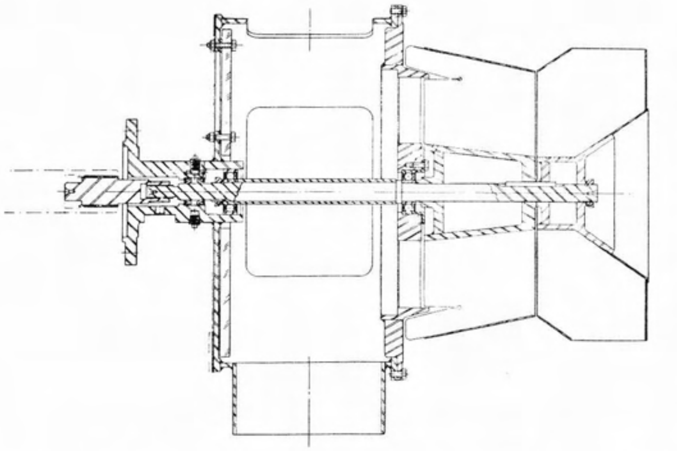
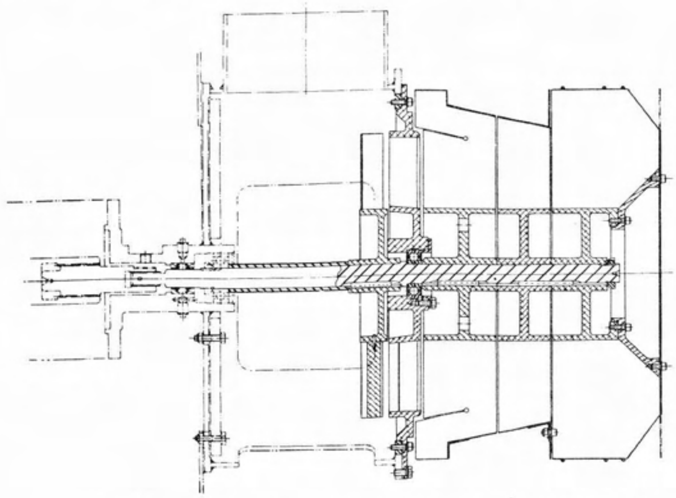


Fig. 8 - X_1 configuration (non-cryogenic test unit)



9 - X_4 configuration (non-cryogenic test unit)

NON-CRYOGENIC TEST DATA - TURBINE PERFORMANCE. Turbine performance for atmospheric air was determined during the non-cryogenic test program. Torque speed curves are shown for the design flow rate of 30 cubic feet per second. The turbine was run with the X_1 separator unit installed and with the separator impeller removed. The torque characteristic with the X_1 separator unit shows the expected effect of separator flow losses. The no-load speed is reduced below that for the turbine only due to high separator flow losses at large rotational speeds.

The turbine data shown is run at a hydrogen equivalent pressure drop of approximately 3 psi across the turbine separator combination.

The second plot shows the pressure drop-volume flow characteristic of the turbine and of the turbine-separator combination. Within the band shown, this characteristic is independent of turbine speed. The hydrogen equivalent pressure drop at the design flow rate is approximately 50% higher than the design point pressure drop, specified at 2 psi. (See Figure 12).

HYDROGEN EQUIVALENT SEPARATOR PERFORMANCE FROM NON-CRYOGENIC DATA. From the non-cryogenic test data the power-speed characteristic of the turbine-separator combination has been established. Tests have been made at hydrogen equivalent inlet quality of approximately 0.75. These results show that the present turbine will drive the separator at approximately 2, 000 RPM at inlet qualities of 75%, accomplishing 99% separation efficiency. These conditions were obtained for a hydrogen vapor flow of 6 pounds per second, and a hydrogen pressure drop of 3 psi across the turbine separator combination. The measured efficiencies of this turbine are in the 20-25% range. Further refinement of the turbine design for the cryogenic models can be expected to increase this efficiency at least 50%. (See Figure 13).

NON-CRYOGENIC TEST PROGRAM. The non-cryogenic test program has established the

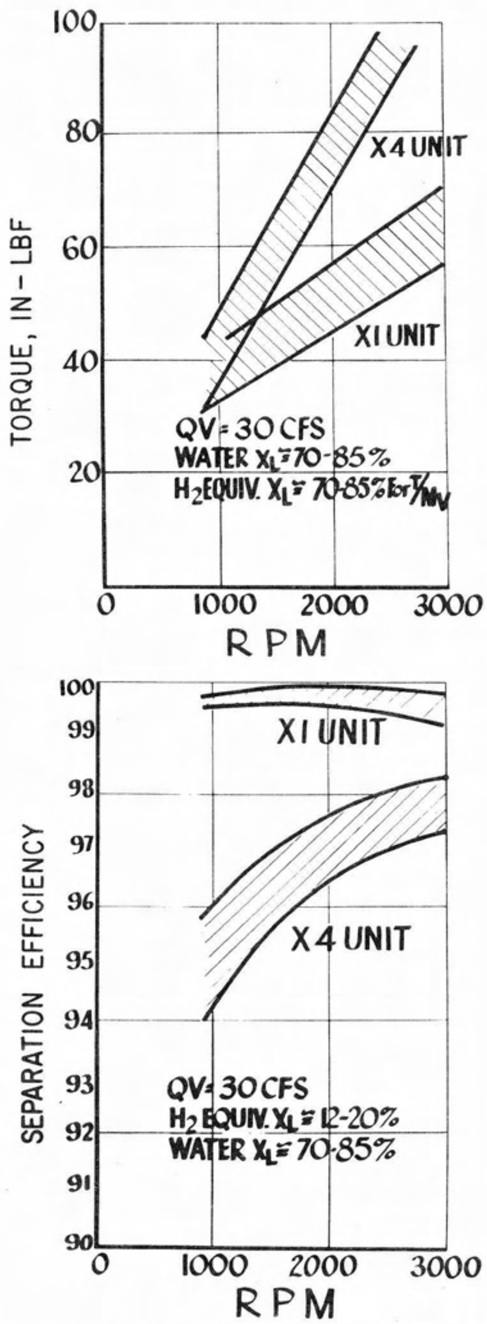


Fig. 10 - Non-cryogenic test data, separator only

following test conclusions:

The X_1 separator design has given better performance than any of the X_4 design variations tested.

The no-load maximum speed of the turbine separator combination will be less than 6, 000 RPM when running at the design flow rate on hydrogen vapor.

Measurements have been made of the separator flow losses. The separator flow losses contribute to the overall pressure drop and are difficult to predict at off-design speeds. These testa have established separator pressure drop over a speed range.

Measured separation efficiencies with water simulation of hydrogen liquid have shown X_1 unit separation efficiencies above 99% at equivalent hydrogen droplet diameters estimated to be down to 0. 2 to 0. 4 inch.

The combined turbine-separator performance characteristic (i. e. speed vs. power) has been established at simulated loads for hydrogen equivalent inlet liquid qualities in the 60-80% range.

For the X_4 unit, the speed effect on separation efficiency has been established; for the

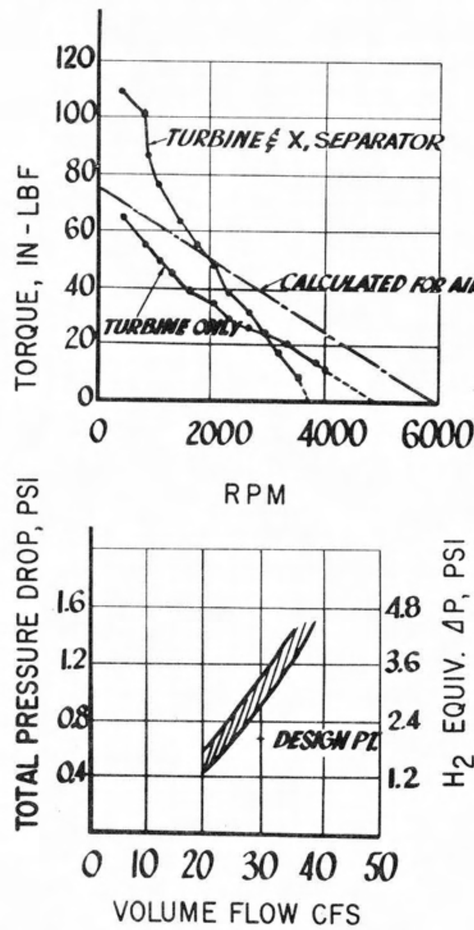


Fig. 11 - Non-cryogenic test data, turbine performance, QAIR = 30 CFS, X_L = O

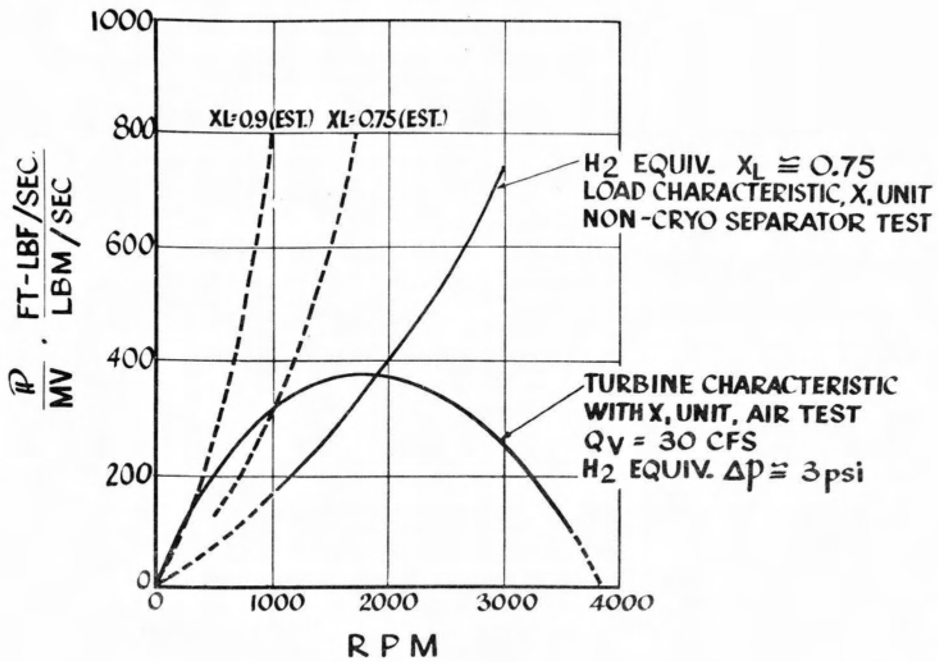


Fig. 12 - H_2 equivalent separator performance from non-cryogenic data

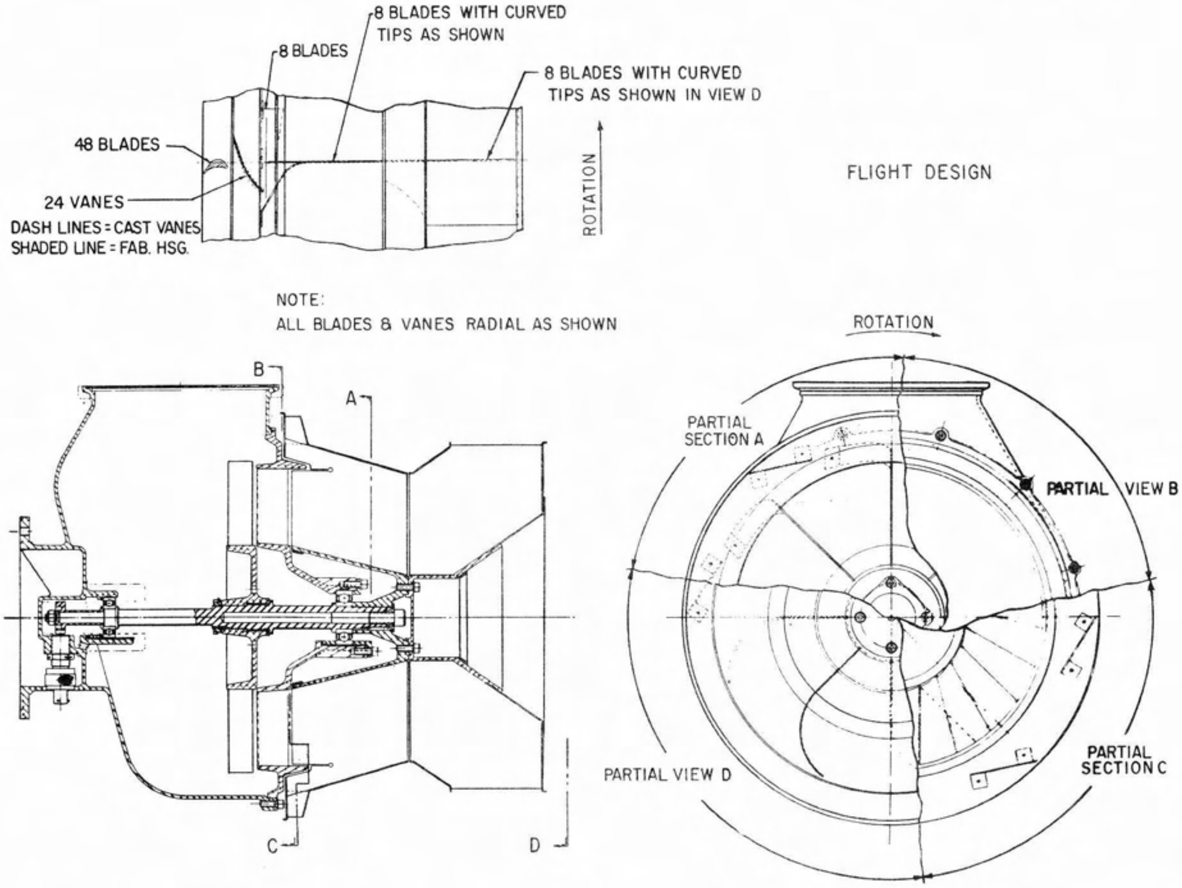


Fig. 13

X_1 unit, separation efficiencies remain high down to 900 RPM.

The flow characteristic (i.e. pressure drop vs. volume flow rate) for the turbine-separator combination has been established. This flow characteristic is essentially independent of speed.

ACKNOWLEDGEMENT

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