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CONVAIR DIVISION OF GENERAL DYNAMICS CORPORATION

REVIEW OF INSTRUMENTATION FOR
CENTAUR FUEL TANK BOIL-OFF
& VENT QUALITY MEASUREMENTS

Contract No. AF18(600)-1775

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Attn: SMSD

PREPARED BY J. Merine
F. Merine

CHECKED BY J. C. Ballinger
J. C. Ballinger
Thermodynamics
Group Engineer

APPROVED BY P. E. Martin
W. B. Mitchell
Asst. Chief Engineer
Design Analysis
APPROVED BY W. F. Radcliffe
W. F. Radcliffe
Chief Engineer-Design

REVISIONS

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FOREWORD

GD/A was requested by NASA-MSFC to review Centaur instrumentation selected for hydrogen boil-off and quality measurements. This report includes a description and limitations of instrumentation, methods of obtaining results, and recommendations for improving the measurement technique. An investigation was also conducted to determine if boil-off measurements were possible with other existing instrumentation.

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SUMMARY

As a result of a meeting with NASA-MSFC (Centaur Heat Transfer Review Meeting, January 4-5, 1962), it was requested that a review be conducted of the instrumentation for hydrogen boil-off and vent fluid quality measurements for the Centaur vehicle. Accurate measurements are important because boil-off and quality reflect the payload losses as affected by heat input and zero-g separator operation, respectively.

Two types of quality are discussed herein: fluid quality and thermodynamic quality. Fluid quality provides a measure of the separator effectiveness for venting vapor. Thermodynamic quality is a measure of the combined separator-heat exchanger effectiveness. This value determines the quantity of hydrogen which must be vented overboard.

The present instrumentation consists of a mass flow meter, liquid detector, and temperature and pressure devices located within the vent system. From this instrumentation, the required information will be obtained if the following conditions exist:

1. The separator must vent mostly vapor as ground tests indicate.
2. The heat exchanger, installed as part of the vent system, must be capable of evaporating up to 30 lb/hr of liquid, as computed.

Fluid quality measurements between 0.77 and 1.00 will be attained within 2%-3%, depending upon the accuracy of ideal gas flow rates. Thermodynamic quality will be measured within 0.21%, and vapor flow rates ranging from 100 lb/hr to 130 lb/hr will be measured within 2% accuracy.

77% 100% VAPOR
slugs ?

The above conditions appear to impose no practical restrictions upon the intended measurements. Ground tests indicate the separator under normal conditions will vent almost 100% vapor; under abnormal conditions, when it no longer functions, almost pure liquid is vented. If large quantities of liquid are vented, accurate measurements will not be possible but it is obvious that separator modifications would be necessary. Additional information would not be needed. Also, the high vent rate represents an extreme flow measurement condition which is unreasonable to attempt.

An investigation was also conducted to determine if boil-off measurements were possible with other existing instrumentation. Usable measurements of second coast period boil-off can be obtained from the liquid-gas sensors. In fact, the sensors will yield the data, from flights F1 and F2, of total hydrogen mass vented during the coast periods.

HET-WIRE (XMAS TREE LIGHTS)

As a result of investigating the vent system instrumentation, it was concluded that the existing instrumentation would be adequate for the existing zero-g vent system. It is anticipated, however, that future vent systems incorporated in the Centaur vehicle will not include a heat exchanger. Therefore the need for a mass flow meter does exist. Efforts are being made by GD/A to initiate a proposal recommending additional testing of the mass flow meter to establish its capability for two phase flow measurements. In addition, it is suggested that tests be conducted to accurately measure the ideal gas flow rate through the separator in order that separator fluid quality of the early Centaur flights may be more accurately determined.

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DISCUSSION

I. REQUIRED MEASUREMENTS

It is important to determine the total quantity of hydrogen which will be vented from the fuel tank during the parking orbit and transfer ellipse of a Centaur mission. The vented fluid represents payload loss and, therefore, reduction of performance.

In general the quantity of fluid vented will be due to:

1. Boil-off resulting from heat transfer to the tank during the coast periods.
2. The effectiveness (or ineffectiveness) of the zero-g separator in separating gas from liquid.

Both boil-off and quality measurements are required. The former represents an expected loss, but one which must be accurately determined for future evaluation of vehicle performance. The latter may represent an unnecessary loss, due to liquid being vented, which must be known in order to improve the effectiveness of the zero-g vent device.

Two types of quality measurements are involved. First, fluid quality of hydrogen entering the separator, which is a measure of separator effectiveness for venting vapor. Second, a thermodynamic quality, which measures the effectiveness of the zero-g vent device. The vent device consists of the separator in series with a heat exchanger. Thermodynamic quality determines the quantity of hydrogen which must be vented overboard during any given venting cycle. Fluid quality is determined from vent flow rate measurements. Thermodynamic quality is determined from vent fluid enthalpy measurements.

II. INSTRUMENTATION

QUALITY METER

The instrumentation for obtaining the required measurements are a liquid detector, mass flow meter, and various pressure and temperature devices. The detector and flow meter are installed in the overboard vent line downstream of the heat exchangers. A pressure transducer is located in the fuel tank and one at the exchanger outlets. A temperature probe at the heat exchanger inlet and a differential temperature transducer across the exchanger complete the instrumentation.

In addition to the above, specific knowledge of the separator and heat exchanger performance is necessary to obtain more complete information from the instrumentation.

The liquid detector is an optical device which will determine the presence of liquid droplets in a gas stream. It consists of a light source to illuminate the droplets and a photo sensor to detect reflections from the droplets. Although measurement accuracy of the device is not known it is estimated that one lb/hr flow of liquid can be detected. Similar systems have been used which can sense the presence of minute liquid droplets. The detector cannot determine fluid quality.

The mass flow meter selected has the potential of measuring mass flow rates of two phase or single phase fluids. It incorporates a rotor having two sets of turbine blades with different blade angles, coupled by a spring and capable of relative angular motion with respect to each other. Measurements can be obtained which are proportional to flow momentum and average fluid velocity. From these a direct measure of mass flow is effected.

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To date the flow meter has been calibrated with a single phase fluid only. It is capable of measuring 80 to 200 lb/hr of gaseous hydrogen within 2% accuracy.

The pressure and temperature measurements will be used to determine enthalpy from which thermodynamic quality will be obtained. From tank pressure will be determined heat of evaporation and enthalpy of saturated liquid which correspond to that pressure. The pressure and temperature measurements of the vent fluid will yield its enthalpy. The measurement accuracies are:

tank pressure	± 0.16 psia
heat exchanger outlet pressure	± 0.08 psia
heat exchanger inlet temperature	$\pm 0.56^{\circ}\text{R}$
heat exchanger differential temperature	$\pm 0.24^{\circ}\text{R}$

The separator has been designed to vent about 100 lb/hr of GH_2 from the Centaur under the expected tank pressure and temperature. These flow rates have been substantiated with ground tests. The design flow rate can be considered as the ideal flow through the separator because if a greater mass flow occurs, liquid is being vented. Less than the ideal flow rate cannot exist for a given set of tank conditions. Using the concept of ideal mass flow, fluid quality measurements of hydrogen entering the separator are possible.

The heat exchangers, which are downstream of the separator, increase the ability of obtaining adequate boil-off and fluid quality data with the present instrumentation. They have a computed capacity for evaporating about 30 lb/hr. of liquid

which may enter the separator. Since the maximum expected flow rate into the separator is 100 lb/hr of GH_2 , the maximum flow rate which can be accurately measured is 130 lb/hr. A greater flow rate would result in two-phase flow through the flow meter. Liquid would be detected and the flow meter would indicate more than 130 lb/hr. Because the flow meter is not as yet calibrated for a fluid mixture, there would be no means available for interpreting the flow measurement.

The heat exchangers also make it possible to measure thermodynamic quality of the fluid exiting the hydrogen tank because these measurements are possible only if 100% vapor exits the exchangers.

III. QUALITY MEASUREMENTS

Fluid quality measurements within the range of interest can be determined with the existing instrumentation because:

- A. The instrumentation is capable of measuring qualities between 0.77 and 1.0
- B. Ground tests have indicated the separator will either operate with no noticeable amount of liquid vented or with a considerable amount of liquid vented.

Quality of fluid entering the separator can be expressed as $x = \dot{W}_{g_1} / \dot{W}_T$ (See Appendix)

where x = fluid quality

$\dot{W}_{g_1}$ = ideal gas flow rate of 100 lb/hr

$\dot{W}_T$ = total fluid flow rate

The limits of accurate fluid quality measurements are for $\dot{W}_T = 100$ lb/hr ($x=1.0$) and $\dot{W}_T = 130$ lb/hr ($x=0.77$). Within these limits fluid quality with an accuracy of 2% will be measured (assuming $\dot{W}_{g_1}$ is known exactly). Should fluid with a quality of 0.77 be vented during the maximum heating trajectory mission, the additional payload loss would be approximately 27 pounds more than venting with a fluid quality of 1.0. Because this payload loss cannot be tolerated the existing quality range is sufficient for evaluating the zero-g separator.

The payload loss attributed to a vent fluid quality of 0.77 is correct only if separator effectiveness alone is considered. The existence of heat exchangers reduces the net loss because of the exchangers ability to transfer energy from tank fluid to vent fluid.

Thermodynamic quality of fluid exiting the tank is defined as,

$$X = \frac{H_x - H_{sl}}{H_{ev}} \quad (\text{see Appendix})$$

where

X = thermodynamic quality

H_x = enthalpy of exiting vent fluid R/lb

H_{sl} = enthalpy of saturated liquid at tank pressure B/lb

H_{ev} = heat of evaporation at tank pressure B/lb

H_x will be measured at the heat exchanger outlet which thermodynamically is the tank exit since energy exchange between vent and tank fluid ceases at the exchanger. H_x will be determined from pressure, temperature, and differential temperature measurements at the exchanger. H_{ev} and H_{sl} will be determined from tank pressure measurements (assuming the liquid is saturated at tank pressure). The accuracy of the quality measurement will be within $\pm 0.21\%$.

The same limitations exist for measuring thermodynamic quality as with fluid quality; vent flow rates cannot exceed 170 lb/hr. The exit enthalpy will be determined from pressure and temperature measurements. However, to measure enthalpy, 100% vapor must exist at the exit because enthalpy measurements for a mixture cannot be found from pressures and temperatures alone. Therefore, quality measurements will be obtained up to vent rates of 130 lb/hr.

IV. VENT FLUID FLOW RATES

The flow meter will adequately and accurately measure the total mass flow of fluid vented during the coast periods if the separator performs within the fluid quality range of 0.77 to 1.0. If the separator does not perform near the 100% quality condition, ground tests indicate mostly liquid will be vented. It is unlikely that a mass flow meter will be developed, in the immediate future which is capable of measuring flow rates over such a wide quality range. In addition, flow measurements in the low fluid quality range are unnecessary because this represents an extreme condition which cannot be tolerated and modifications of future separators would be made to prevent recurrence.

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V. OTHER METHODS OF MEASURING BOIL-OFF

An investigation was made to determine if existing instrumentation could be used for measuring the total quantity of hydrogen vented during coast periods. The two instruments capable of this measurement are the low-g accelerometer and the liquid-gas sensors. The accelerometer is able to measure the difference between vehicle weights at the beginning and following a coast period within an accuracy of 300-500 lbs. The accuracy is unsuitable for Centaur application. The sensors must detect the liquid level before and after a coast period. A calculation indicated that the hydrogen measurement error would be ± 34.6 lbs and ± 30 lb. for the first and second coast periods respectively, assuming a liquid level sensing accuracy of $\pm 1/2$ inch. A hydrogen error of 15 lb. is included because of the uncertainty of the hydrogen mass required for pump chilldown. A maximum of 25 lb. and 127 lb. of hydrogen are expected to be vented overboard during the first and second coast periods of a typical Centaur vehicle. Hence, only for second coast period boil-off can the sensors furnish usable data.

VI. EXPECTED F-1 & F-2 FLIGHT TEST RESULTS

Telemetered data from F-1 and F-2 flights will yield sufficient information to determine fluid quality entering the zero-g separator within the limits previously discussed. The total mass of hydrogen vented will not be known, however, because large quantities will be vented through a tube by-passing the flow measurements. Even if all hydrogen was vented through a common line, flow measurements still could not be obtained because a flow meter is not available to measure the high flow rates expected. For these flights, however, the liquid sensors will yield the total overboard hydrogen flow within the error limits previously discussed.

VII. CONCLUSIONS

The existing instrumentation appears to be adequate for evaluating hydrogen boil-off, the effectiveness of the separator and separator-heat exchanger combination to vent vapor only. Support testing is needed, however, to improve fluid quality measurement accuracy and to determine the capabilities of the mass flow meter.

Fluid quality measurements are dependent upon the ideal gas flow rate through the separator. Presently this value is known only approximately. Tests should be conducted to accurately determine the ideal flow rate for all separators.

Presently mass flow measurements are dependent upon 100% vapor flow through the separator or a 50 lb/hr computed evaporation rate of liquid. The mass flow meter should remain free of limitations upon its performance and hence should be capable of measuring the mass flow of a hydrogen mixture. This will be especially true if future vent systems are not equipped with heat exchangers to evaporate liquid vented overboard. It is imperative that capabilities exist for measuring mass flow rates of liquid-gas mixtures in order to adequately evaluate future zero-g vent systems. Therefore, efforts are being made by GD/A to initiate a proposal recommending additional flow meter tests to establish its capabilities for two phase flow measurements.

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Flights P-1 and P-2 should yield sufficient information to evaluate separator performance. But total vent flow will not be obtained from vent system instrumentation, because fluid vented through the boil-off valve will b.-pass the instrumentation. For these flights, however, the liquid sensors will yield the total overboard hydrogen flow.

APPENDIX

QUALITY MEASUREMENTS OF VENTED HYDROGEN

Fluid Quality

Fluid quality in a flow stream is defined as

$$x = \dot{w}_g \div (\dot{w}_g + \dot{w}_L) = \frac{\dot{w}_g}{\dot{w}_T} \quad (1)$$

where x = fluid quality

$\dot{w}_g$ = gas mass flow rate

$\dot{w}_L$ = liquid mass flow rate

$\dot{w}_T$ = total mass flow rate

A slight modification of equation (1) can be used to determine the quality of hydrogen entering the zero-g separator.

It has been determined that an ideal gas flow rate of 100 lb/hr will exist through the separator with LH₂ tank conditions of 21 psia and 38.8°R. A greater mass flow rate is an indication that liquid droplets exist in the gas stream. Assuming the volumetric flow of fluid vented is constant for small quantities of liquid in the gas stream, we have:

$$\dot{V}_g + \dot{V}_L = \dot{V}_{gi} \quad (2)$$

where $\dot{V}_{gi}$ = ideal GH₂ volumetric flow rate 926 ft³/hr

$\dot{V}_g$ = GH₂ volumetric flow rate ft³/hr

$\dot{V}_L$ = LH₂ volumetric flow rate ft³/hr

The heat exchangers, downstream of the separator, are capable of evaporating 30 lb/hr of LH_2 . This is the maximum liquid flow rate which can accurately be measured by the flow meter and, therefore, the lowest quality which can be measured. The liquid flow rate is equivalent to a volume flow of $6.8 \text{ ft}^3/\text{hr}$.

Solving for $\frac{\dot{V}_g}{\dot{V}_{gi}}$ from equation (2),

$$\frac{\dot{V}_g}{\dot{V}_{gi}} = 1 - \frac{\dot{V}_L}{\dot{V}_{gi}} = 1 - .0073 \approx 1.0$$

$$\frac{\dot{V}_g}{\dot{V}_{gi}} = \frac{W_g/\rho_g}{W_{gi}/\rho_g} = \frac{\dot{W}_g}{\dot{W}_{gi}} = 1.0$$

Therefore $\dot{W}_{gi} = \dot{W}_g$ (3)

Substituting equation (3) into (1),

$$x = \frac{\dot{W}_{gi}}{\dot{W}_r} \quad (4)$$

Since $\dot{W}_{gi}$ is known, only $\dot{W}_r$ is required to determine quality.

The accuracy of the quality measurement can be found by operating on equation (4)

$$\frac{dx}{x} = \sqrt{\left(\frac{d\dot{W}_{gi}}{\dot{W}_{gi}}\right)^2 + \left(\frac{d\dot{W}_r}{\dot{W}_r}\right)^2} \quad (5)$$

$$\left(\frac{d\dot{W}_r}{\dot{W}_r}\right) = .02 \text{ (given from flow meter accuracy)}$$

$$\frac{d\dot{W}_{gi}}{\dot{W}_{gi}} = \text{unknown}$$

If $\frac{d\dot{W}_{gi}}{\dot{W}_{gi}} = 0$ $\frac{dx}{x} = .02 = 2\% \text{ uncertainty.}$

If $\frac{d\dot{W}_{gt}}{\dot{W}_{gt}} = .02$ (assuming same flow meter accuracy as for flight)

$$\frac{dX}{X} = .028 = 2.8\% \text{ uncertainty.}$$

Thermodynamic Quality

Thermodynamic quality of a fluid mixture is defined as

$$X = \frac{H_x - H_{sl}}{H_{sv} - H_{sl}} = \frac{H_x - H_{sl}}{H_{ev}} \quad (6)$$

where X = thermodynamic quality

H_x = enthalpy of fluid mixture B/lb

H_{sl} = enthalpy of saturated liquid @ reference pressure B/lb

H_{sv} = enthalpy of saturated vapor @ reference pressure B/lb

H_{ev} = heat of evaporation @ reference pressure B/lb.

This definition can be applied to a superheated fluid as well as by re-defining H_x . Thus,

H_x = enthalpy of fluid (super heated or mixture) B/lb

Because the measurement will reflect the thermodynamic quality of fluid exiting the Centaur fuel tank, both H_{sl} and H_{ev} are values which will be referenced to fuel tank pressure, and, H_x is the enthalpy of the fluid exiting the fuel tank. Operating on equation (6) to determine measurement accuracy we have,

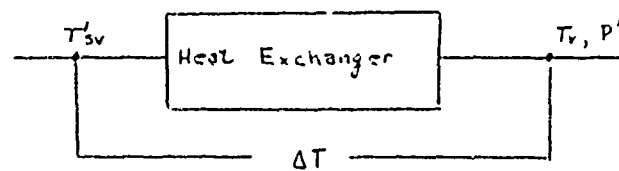
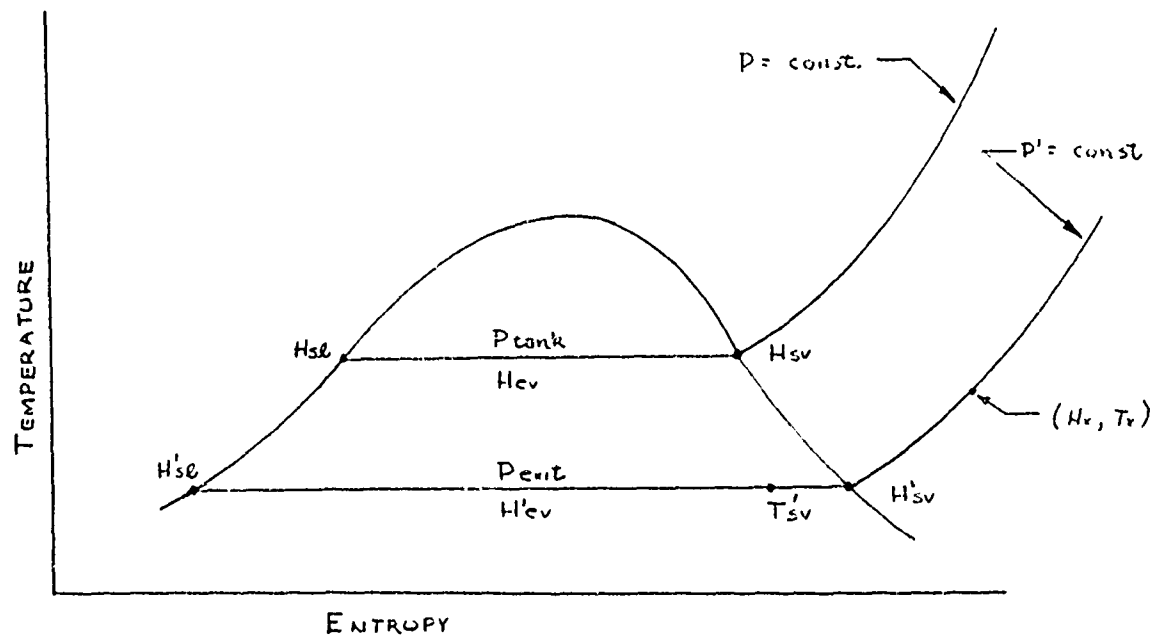
$$\frac{dX}{X} = \sqrt{\left(\frac{dH_x}{H_x - H_{sl}}\right)^2 + \left(\frac{dH_{ev}}{H_{ev}}\right)^2 + \left(\frac{dH_{sl}}{H_x - H_{sl}}\right)^2} \quad (7)$$

Both H_{ev} and H_{sl} remain essentially constant in the region of interest. Consequently, as an approximation, $dH_{ev} = 0$ and $dH_{sl} = 0$.

Therefore

$$\frac{dX}{X} = \frac{dH_x}{H_x - H_{sl}} \quad (8)$$

Before equation (8) can be evaluated, the role of the heat exchanger and related instrumentation should be discussed. A schematic of the exchanger and vent fluid state properties are given below.



The vent fluid mixture which exits the separator will enter the exchanger at temperature T'_{sv} . Heat transfer from the tank fluid, while flowing through the heat exchanger, will evaporate the venting liquid and perhaps increase vent fluid temperature; under the expected vent conditions all liquid should evaporate before leaving the exchanger. A differential temperature transducer will measure temperature rise across the exchanger and a liquid detector will detect the presence of droplets in the vent gas stream. In order for enthalpy measurements to be valid, 100% vapor must exit the exchanger. Therefore the detector must "read" vapor. When ΔT (the differential temperature rise) is zero, a saturated vapor at enthalpy H'_{sv} exits the exchanger; H'_{sv} , will be determined from a absolute pressure measurement. Should ΔT be greater than zero the vapor will be super heated at temperature T_x and the enthalpy H_x will be found from the pressure and differential temperature measurements.

To determine quality measurement error, the following was performed:

$$\begin{aligned} H_x - H_{sl} &= (\Delta H_x + H'_{sv} - H_{sl}) + (H'_{sl} - H'_{sv}) \\ &= (H'_{sv} - H'_{sl}) + [\Delta H_x + (H'_{sl} - H_{sl})] \\ &= H'_{cv} + [\Delta H_x + (H'_{sl} - H_{sl})] \end{aligned} \quad (9)$$

where H'_{cv} = heat of evaporation of exit pressure B/lb
 H'_{sv} = saturated vapor enthalpy at exit pressure B/lb
 H'_{sl} = saturated liquid at exit pressure B/lb
 ΔH_x = exit fluid differential super heat enthalpy B/lb.

The terms within the bracket are small and may become negligible by virtue of having opposite signs. Thus

$$(H_x - H_{sl}) \approx H'_{cv} \quad (10)$$

$$\begin{aligned}\text{Also, } dH_v &= d[\Delta H_x + H'_{sv}] = d[C_p (T_x - T'_{sv}) + H'_{sv}] \\ &= d[C_p \Delta T + H'_{sv}] \\ &= C_p d(\Delta T) + d(H'_{sv})\end{aligned}$$

The error in determining H'_{sv} will be quite small because very accurate pressure measurements will be obtained. Therefore, $d(H'_{sv}) \approx 0$ and,

$$dH_x = C_p d(\Delta T) \quad (11)$$

Inserting equations (10) and (11) into (8)

$$\frac{dX}{X} = \frac{C_p d(\Delta T)}{H'_{cv}} = .0021 = .21\% \quad (12)$$

when exit pressure is 2.0 psia and the differential temperature accuracy is $\pm 0.16^\circ\text{R}$.

The quality measurement error may be as great as 0.3% if the other small measurement errors are included.

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