BELLCOMM, INC.

SUBJECT: Cryogenic Liquid Hydrogen Storage for Manned Mars Missions - Case 103-2

DATE: March 15, 1966

FROM: C. E. Johnson

ABSTRACT

Martin data are used and scaled as a comparison to TRW results in their Mission Oriented Advanced Nuclear System Parameters Study (Refs. 1, 2). Martin assumptions are examined and accounted for in scaling in an attempt to make conservative predictions for the middle/late 1970's. Because the problem of liquid hydrogen boiloff is one which could have a strong differential effect on a nuclear/chemical propulsion comparison for a manned Mars mission, boiloff penalties for nuclear stages III (Mars braking) and IV (Mars depart) of the TRW study were checked and results indicate that realistic values for cryogenic boiloff and insulation weights were used. Also, the total boiloff and insulation weight penalty for a completely passive nuclear storage system for LH_2 at its normal boiling point, for the outbound leg of a TRW Mars mission, is less than 10% of the stored propellant.

(NASA-CR-153571) CRYOGENIC LIQUID HYDROGEN STORAGE FOR MANNED MARS MISSIONS (Bellcomm, Inc.) 17 p

N79-72605

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MEMORANDUM FOR FILE

INTRODUCTION

The problem of liquid hydrogen boiloff is one which could have a strong differential effect on a nuclear/chemical propulsion comparison for a manned Mars mission. Nuclear stages contain 100% LH_2 whereas cryogenic chemical stages can contain anywhere from 6 to 16%. Parametric studies have indicated that if LH_2 boiloff were to reach 30 to 40% nuclear stages would actually be worse for Mars braking and escape than cryogenic chemical stages. In performing the nuclear/chemical comparison a TRW study is currently being critiqued.[1] To check the TRW values for boiloff, detailed studies of this problem which have been carried out by NASA contractors, have been examined to derive estimates of the weight penalties involved for the long term storage of LH_2. Martin (Baltimore, Md.) appears to have performed the most comprehensive study of significant depth and, therefore, boiloff results from this study are used and scaled to the TRW mission as a comparison.[2] Specifically, the LH_2 boiloff penalties for TRW nuclear stages III (arrive Mars), and IV (depart Mars) are checked. This comparison is based solely on a completely passive insulation system for storing cryogenic fuel at its normal boiling point, namely the use of multilayer or superinsulation (ML1). ML1 consists of a number of highly reflective foils (Aluminum or Aluminized Mylar) laid layer upon layer upon themselves to form a blanket of multiple radiation shields. Ideally, in a vacuum the only mode of heat transfer is radiation and it is therefore, theoretically possible to efficiently reduce the flow of heat to a cryogenic tank to a very low value. In fact, incidental heat leakages through pipes, insulation seams, tank supports, and other penetrations can easily predominate and must be carefully controlled if they are not to nullify the effectiveness of the insulation system. Martin appears to have realistically considered the ML1 heat-leak problem based on the current state of the art.

However, since the higher energy advantage of cryogenic propellants makes them extremely desirable for propulsion systems, current efforts should be continued to refine the analytical treatment of heat-leak factors by the generation of more experimental data. Some of the uncertainty that is presently existing in the determination of these factors would thereby be reduced.

Two methods were proposed by Martin that complement the above passive insulation system. Active tank supports that retract under low load conditions, in conjunction with stainless steel or titanium suspension wires which offer low areas and long paths for heat conduction, can theoretically reduce LH_2 boiloff by a factor of approximately 2.3 during the outbound leg of a Mars mission. Additional work should be done however, to reduce the complexity involved and to devise methods of preventing heat-leak shorts at the wire/ML1 joints. Secondly, presubcooling the LH_2 together with some superinsulation could reduce the boiloff to zero. For example, if enough insulation were applied to allow the normal boiling point of the propellant to be reached at engine fire, insulation mass would be the only stage mass penalty with this technique. Work must also be done in this area to devise efficient methods to cool the LH_2.

The Martin data incorporate projected heat-leak minimums for an active support system with stainless steel suspension wires, and presubcooling is not used. In this comparison, the data are modified to a present-day hard-mount titanium-tank-support system in an effort to be conservative in predicting values for the middle/late 1970's. Therefore, in drawing conclusions from the final results, it must be kept in mind that theoretically these values could be significantly reduced if one of the two or both additional modes of storage are employed.

Theory

Nomenclature:

W_{BO} = Boiloff Weight

W_i = Insulation Weight

W_{PL} = Payload Weight

W_P = Cryogenic Propellant Weight

V = Cryogenic Propellant Volume

W_{ST} = Stage Structure Weight

W_G = Stage Gross Weight

ΔV = Stage Velocity Increment

I = Specific Impulse

K = Effective Thermal Conductivity of Superinsulation

A = Surface Area

ΔT = Temperature Difference

τ = Propellant Storage Time

h = Latent Heat of Vaporization of Propellant

t = Insulation Thickness

ρ_i = Insulation Density

ρ_p = Propellant Density

g = Universal Gravity Constant, Earth

C = Arbitrary Constant

$r = e^{\Delta V/Ig}$

$W_{BO}(\%)$ = Percent Boiloff Weight

$W_i(\%)$ = Percent Insulation Weight

For storage of cryogenic propellants required for the terminal stage of a vehicle, the insulation and boiloff masses are affected by the given stage energy requirement or velocity increment (ΔV) and the propellant-engine available energy or specific impulse (I). An expression can be derived to relate the boiloff and insulation weights for optimum vehicle performance or maximum payload for a given stage as follows -

The stage gross mass can be defined as -

$$W_G = W_{PL} + W_P + W_{ST} + W_i \tag{1}$$

The stage velocity increment at engine fire is defined as -

$$\Delta V = gI \ln \left(\frac{W_G - W_{BO}}{W_G - W_P} \right) \tag{2}$$

Equation (2) can be written as -

$$\frac{W_G - W_{BO}}{W_{PL} + W_{ST} + W_i} = e^{\Delta V/Ig} = r$$

or

$$W_{PL} = \frac{W_G}{r} - W_{ST} - W_i - \frac{W_{BO}}{r}. \tag{3}$$

Boiloff weight can be expressed as -

$$W_{BO} = \frac{KA\Delta T\ \tau}{ht} \tag{4}$$

Insulation weight can be expressed as -

$$W_i = \rho_i At \tag{5}$$

From (4) and (5) the boiloff weight can be expressed in terms of insulation weight as -

$$W_{BO} = \frac{KA^2 \Delta T \tau \rho_i}{h\ W_i} = \frac{C}{W_i} \tag{6}$$

where, $C = \dfrac{KA^2 \Delta T \tau \rho_i}{h}$

Holding the initial stage gross mass in earth orbit constant, the payload is maximized when the derivative of equation (3) with respect to insulation weight is set equal to zero. Substituting (6) into (3) and differentiating, the expression relating boiloff and insulation weight for optimum vehicle performance can be written finally as -

$$\frac{W_{BO}}{W_i} = r = e^{\Delta V/Ig} \tag{7}$$

The same relation is obtained if W_G is minimized with respect to W_i, holding W_{ST} and W_{PL} constant.

In both the TRW and Martin studies equation (7) was used to determine optimum insulation weights for the storage of cryogenics. In the TRW study (7) was further modified to account for size, number, and time of vehicle propulsive velocity changes. However, the direct use of equation (7) is sufficient for the purpose of this comparison. Applying equations (4), (5), and (7) expressions for percent boiloff and percent insulation weights with respect to tank-surface-area-to-volume ratios and stored-propellant weight can be derived.

$$W_P = V\rho_P \tag{8}$$

From (5), (7), and (8) -

$$\frac{W_{BO}}{W_P} = \frac{At\rho_i e^{\Delta V/Ig}}{V\rho_P}$$

The optimum insulation thickness (t_{opt}) can therefore be expressed as -

$$t_{opt} = \frac{W_{BO}}{W_P} \frac{V\rho_P}{A\rho_i e^{\Delta V/Ig}} \tag{9}$$

From (4) and (8) -

$$\frac{W_{BO}}{W_P} = \frac{KA\ \Delta T\tau}{ht\ V\rho_P} \tag{10}$$

Substituting the expression for t_{opt} into (10) -

$$W_{BO}(\%) = \left(\frac{K\Delta T\rho_i}{h\rho_P^{\ 2}}\right)^{1/2} \frac{A}{V} \ (\tau r)^{1/2}\ 100 \tag{11}$$

or

$$W_{BO}(\%) = C_1 \frac{A}{V} (\tau r)^{1/2} \tag{12}$$

where,
$$C_1 = \left(\frac{K\Delta T\rho_i}{h\rho_P^{\ 2}}\right)^{1/2} 100$$

From (12) and (7)

$$W_i(\%) = C_1 \frac{A}{V} \left(\frac{\tau}{r}\right)^{1/2} \tag{13}$$

Scaling laws can therefore be written, where the primes refer to separate vehicles, as -

$$W_{BO}''(\%) = \frac{W_{BO}'(\%)}{\frac{A'}{V'}\ (\tau' r')^{1/2}} \ \frac{A''}{V''}\ (\tau'' r'')^{1/2} \tag{14}$$

$$W_i''(\%) = \frac{W_i'(\%)}{\frac{A'}{V'}\ \left(\frac{\tau'}{r'}\right)^{1/2}} \ \frac{A''}{V''}\ \left(\frac{\tau''}{r''}\right)^{1/2} \tag{15}$$

Similarly, scaling laws for spherical tanks can be written as -

$$W_{BO}''(\%) = \frac{W_{BO}'(\%) W_P'^{\ 1/3}}{(\tau' r')^{1/2}} \ \frac{(\tau'' r'')^{1/2}}{W_P''^{\ 1/3}} \tag{16}$$

$$W_i''(\%) = \frac{W_i'(\%) W_p'^{\,1/3} r'^{\,1/2}}{\tau'^{\,1/2}} \quad \frac{\tau''^{\,1/2}}{W_p''^{\,1/3} r''^{\,1/2}} \qquad (17)$$

Martin/TRW Comparison

The percent boiloff and insulation penalty data to be compared, as listed in Appendix C, "Supporting Data", (ER 13919-C) p. V-1 of reference 2, and Volume II, "Detailed Technical Report Mission and Vehicle Analysis", p. III 67 of reference 1 are shown in Table I. The Martin data are for a Mars-landing conjunction-class short-stay mission in 1975. Of all the mission types that Martin investigated, it is felt that the integrated heat-intensity profile for this mission most closely approximates that studied by TRW. To determine the values of r for TRW stages III and IV, a nuclear specific impulse of I = 800 sec and typical 1982 velocity increments for Mars braking and escape of ΔV_{MB} = 14200 fps and ΔV_{ME} = 13770 fps were used.

TABLE I

Mission	Martin Configurations				TRW Stage III	TRW Stage IV
r	1.86	1.86	1.81	1.81	1.735	1.705
Time (hrs)	16656	16656	16656	16656	5260	5730
LH_2 (lbs)	15717	38471	6608	12852	310166	219281
Boiloff (lbs)	1691	3166	822	1314	11689	12147
Insul. (lbs)	1297	2518	934	1575	7940	4519
$W_{BO}(\%)$	10.75	8.23	12.42	10.22	3.77	5.54
$W_i(\%)$	8.25	6.54	14.10	12.25	2.56	2.06

Three basic assumptions were made by Martin in deriving the above values -

1. The storage tanks are spherical
2. Heat leaks can be minimized by the use of rigid-retractable/stainless-steel wire supports for the tanks.
3. The state of the art of minimizing heat leak values will improve by the middle/late 1970's and therefore present predicted minimums can be reduced by 36.7%.

Boiloff and insulation weight are directly proportional to surface area and therefore, in accounting for assumption 1, the relationship for the surface area of a constant volume cylindrical tank with hemispherical heads versus the dimensionless parameter R/ℓ was examined. R is the radius and ℓ is the length of the cylindrical portion of the tank. A plot of this relationship is shown in Figure 1. Per page III-70 of the TRW study (Ref. 1), typical cylindrical storage tanks with geometries $R/\ell \gtrsim 1/2$ are used for stages III and IV and therefore, the Martin data should be increased by a factor of ≈ 10%. In accounting for assumptions 2 and 3, if hard-mount titanium-tension straps are employed and a projected state-of-the-art factor not employed, per the Martin study the results in Table I should be modified by a factor of 51/22.6 = 2.26 (Ref. 2, p.20, Final Review). Equations (14) through (17) can be written to include the appropriate modification factors as -

$$W_{BO}''(\%) = \frac{2.26\ W_{BO}'(\%)}{\frac{A'}{V'}\ (\tau' r')^{1/2}} \quad \frac{A''}{V''}(\tau'' r'')^{1/2} \tag{18}$$

$$W_i''(\%) = \frac{W_i(\%)}{\frac{A'}{V'}\left(\frac{\tau'}{r'}\right)^{1/2}} \cdot \frac{A''}{V''}\left(\frac{\tau''}{r''}\right)^{1/2} \tag{19}$$

$$W_{BO}'' = \frac{2.48\ W_{BO}'(\%)\ W_P'^{\,1/3}}{(\tau' r')^{1/2}} \quad \frac{(\tau'' r'')^{1/2}}{W_P''^{\,1/3}} \tag{20}$$

$$W_i''(\%) = \frac{1.10\ W_i'(\%)\ W_P'^{\ 1/3}\ r'^{\ 1/2}}{\tau'^{\ 1/2}} \quad \frac{\tau''^{\ 1/2}}{W_P''^{\ 1/3}\ r''^{\ 1/2}} \tag{21}$$

Applying the Martin data from Table I and averaging, the above scaling laws can finally be written as -

$$W_{BO}(\%) = 0.416\ (\tau r)^{1/2}\ \frac{A}{V} \tag{22}$$

$$W_i(\%) = 0.324\left(\frac{\tau}{r}\right)^{1/2}\ \frac{A}{V} \tag{23}$$

$$W_{BO}(\%) = 3.61\ \frac{(\tau r)^{1/2}}{W_P^{\ 1/3}} \tag{24}$$

$$W_i(\%) = 2.82\ \frac{1}{W_P^{\ 1/3}}\ \left(\frac{\tau}{r}\right)^{1/2} \tag{25}$$

Plots of equations (22) through (25) are shown in Figures 2 through 5 for use in feasibility studies and preliminary design.

Using equations (22) through (25), or the attached plots, the Martin data are scaled against the TRW results for Stages III and IV and are shown finally in Table II.

TABLE II

Stage	% Boiloff		% Ins Weight		Total % Weight Penalty	
	Martin	TRW	Martin	TRW	Martin	TRW
III	5.11	3.77	2.29	2.56	7.40	6.33
IV	5.95	5.54	2.73	2.06	8.68	7.60

Comparing the TRW results with the scaled Martin data, it is seen that the TRW percent boiloff plus insulation weight penalty is approximately 1.4% less than the Martin results. It should be remembered that in drawing conclusions, for the middle/late 1970's, the boiloff values can theoretically be substantially reduced if a retractable support system is used (as can be seen by the above modification factors) or the technique of cryogenic presubcooling employed.

Conclusions

1. TRW appears to have used realistic values for cryogenic boiloff and insulation weights in their Mission Oriented Advanced Nuclear System Parameters Study for manned Mars missions in the early 1980's.

2. The total boiloff and insulation weight penalty for a completely passive nuclear storage system for LH_2 at its normal boiling point, for the outbound leg of a TRW Mars mission, is less than 10% of the stored propellant.

3. It appears that boiloff and insulation weight penalties can be reduced beyond that which can be passively achieved with superinsulation by the method of cryogenic presubcooling, or using a retractable-rigid/wire tank support system.

C. E. Johnson

2024-CEJ-csh

Attachments
References
Figures 1 through 5

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(see next page)

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Messrs. P. E. Culbertson - NASA/MTL
F. P. Dixon - NASA/MTY
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J. A. Hornbeck
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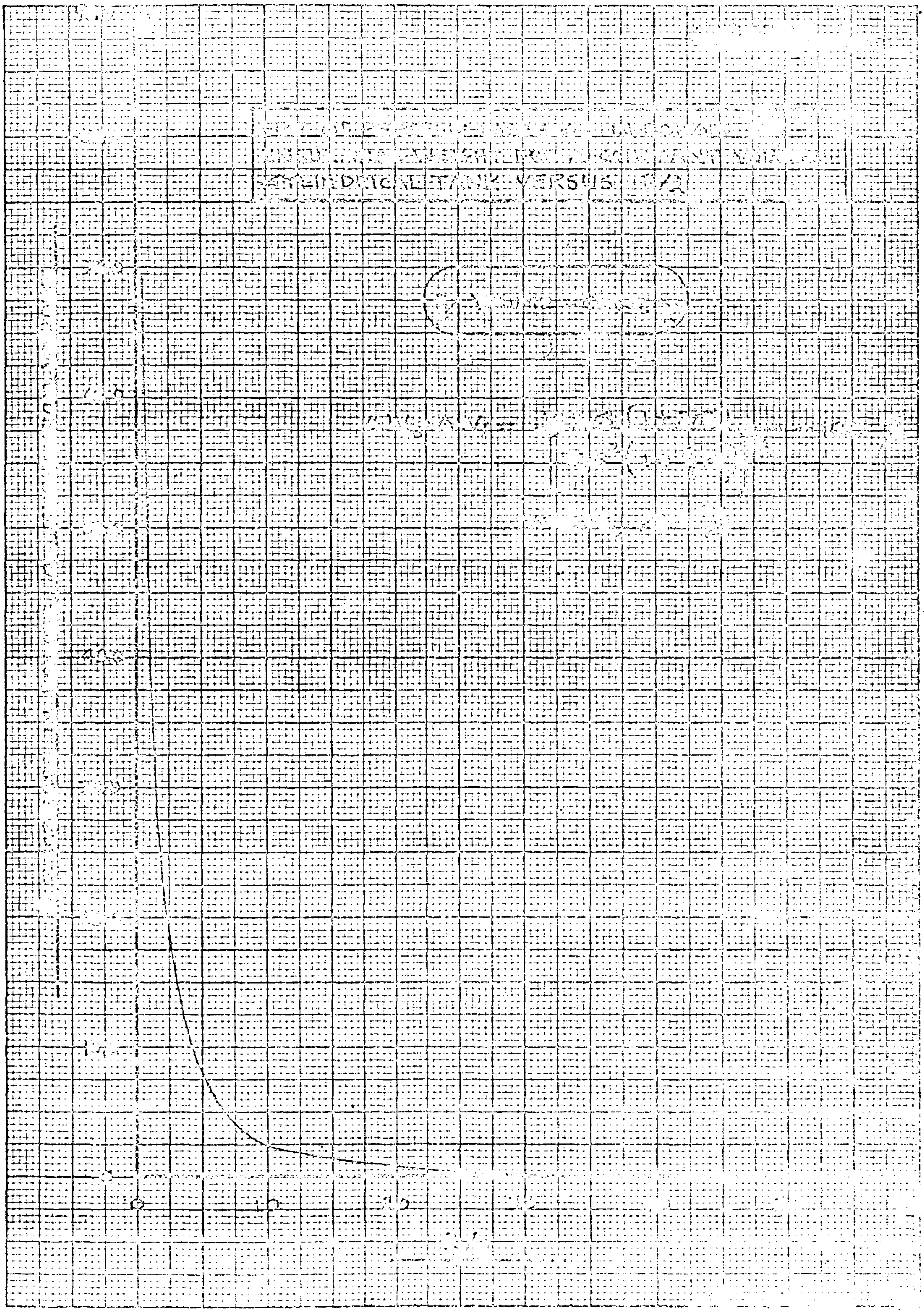
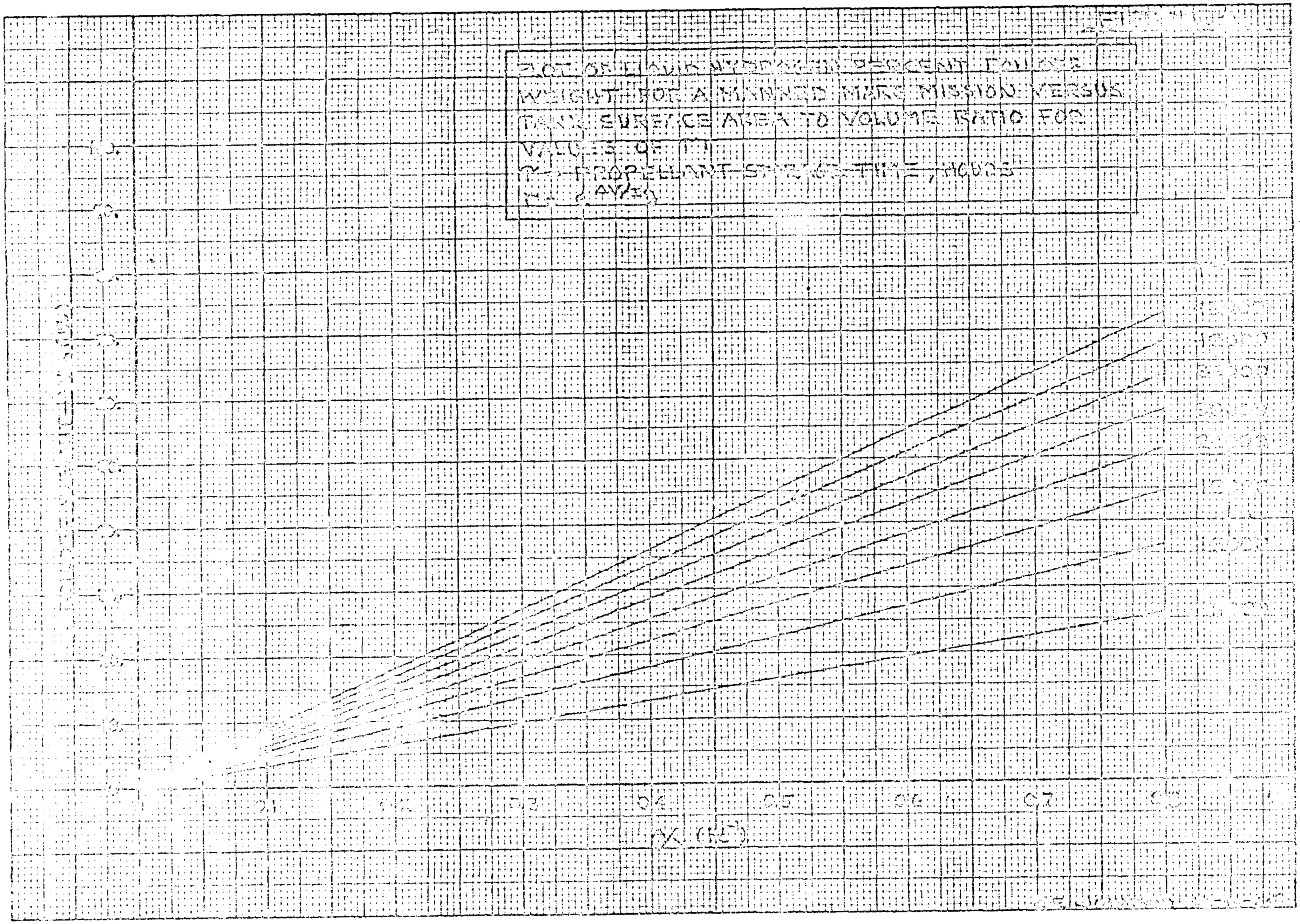
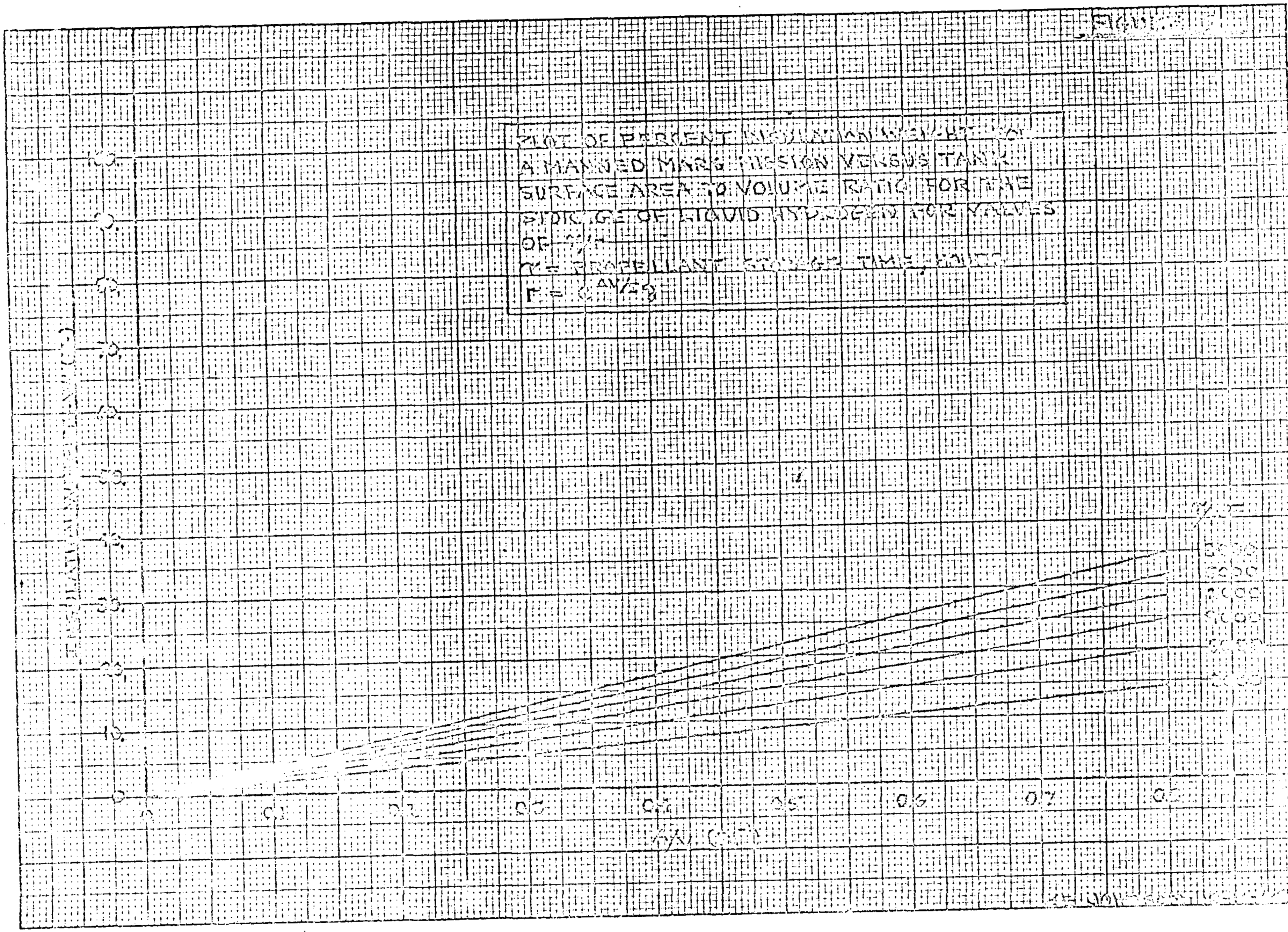
1. Mission Oriented Advanced Nuclear System Parameters Study, Report No. 8423-6006-RU000, TRW Space Technology Laboratories for George C. Marshall Space Flight Center under Contract NAS8-5371, March 1965.

2. Spacecraft Propulsion Systems for Manned Mars and Venus Missions, ER 13919, Martin Baltimore for the Advanced Manned Missions Program Office of the NASA under Contract NASw-1053, July 1965.




WEIGHT FOR A MANNED MARS MISSION VERSUS
TANK SURFACE AREA TO VOLUME RATIO FOR
VALUES OF
PROPELLANT
HOURS


A MANNED MARS MISSION VERSUS TANK
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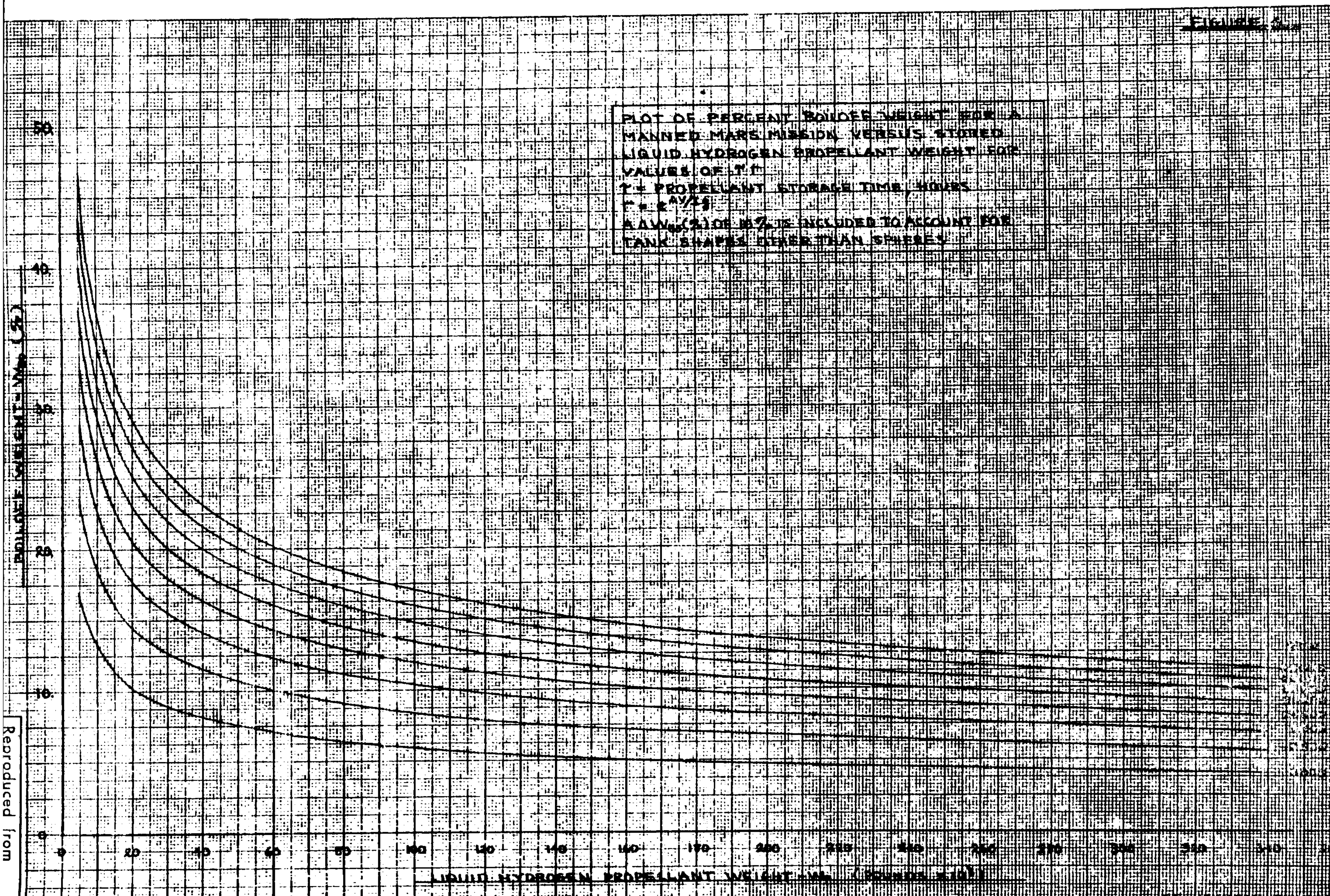
PLOT OF PERCENT BOILOFF WEIGHT FOR A
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