Engineering Notes

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Thermal Structural Optimization of Cryogenic Storage Systems

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Nomenclature

A	= heated area
B, C	= constants defining a saturation curve
C_p	= specific heat
$k_1(t)$	= effective heat-transfer coefficient across all insulation layers
K_2	= storage tank weight to design pressure proportionality constant
L	= latent heat of vaporization
$M(t)$	= propellant weight
M_0	= propellant mass conserved due to heat stored in the propellant bulk ($W_{BO} - W_B$)
p	= storage tank design pressure less NPSH requirements
Δp	= NPSH pressure requirements
p_0	= storage tank initial pressure
Q	= heat stored in the propellant
$q(x, t)$	= propellant heat-transfer rate
r	= tank radius
s	= height of tank cylindrical section
T	= propellant temperature
$T(t)$	= insulation outside surface temperature
T_0	= propellant initial temperature
t, t_1	= time, time of venting initiation
t_2, t_v	= end of mission, external insulation venting time
V	= tank volume
W	= total system weight
W_{ES}, W_{IS}	= external, internal insulation weight
W_B, W_{BO}	= boiloff and maximum propellant boiloff
W_T	= storage tank structural weight
W_I	= total insulation weight ($W_{ES} + W_{IS}$)
x, x_0	= external, internal insulation thickness
ρ, ρ_0, ρ_1	= skin, internal, external insulation density
$\sigma_x, \sigma_\theta, \sigma$	= axial, circumferential, allowable stress

MANY of the vehicles designed for orbital or space operations require cryogenic propellants during large portions of the mission. Some of the vehicles, such as the currently considered reusable space shuttle, have a variety of systems that require both liquid hydrogen and liquid oxygen during boost, orbital coast, re-entry, and cruiseback phases of the mission. In such vehicles, the cryogenic systems represent a significant portion of the vehicle weight. In a typical cryogenic storage system (Fig. 1), the heat input into the propellant can be stored in the bulk of the propellant by allowing the tank pressure to increase or the propellant can be allowed to boil off and the pressure kept constant. In a most general case, both modes can be used to accommodate the heat input into the propellant. In this way, pressure can be allowed to increase during the initial phases of the mission, then system venting initiated at some optimum time t_1. To optimize such a system, the external insulation thickness, internal insulation thickness, and the time of venting initiation that result in the minimum total system weight penalty must be determined. The total weight penalty can be represented as

$$W = W_{ES} + W_{IS} + W_B + W_T$$

where

$$W_{ES} = \rho_1 A x, \quad W_{IS} = \rho_0 A x_0$$

$$W_B = \frac{1}{L}\int_{t_2}^{t_1} A q(x,t)\,dt \quad \text{and} \quad W_T = K_2(p - p_0) + K_2 \Delta p \tag{1}$$

Assuming that all the heat input in the tank is input into the liquid,

$$dT = A[q(x,t)/M(t)C_p]dt \tag{2}$$

Combining Eqs. (1) and (2) and a propellant saturation temperature-pressure relationship of the form $T = Cp^B$, the weight of the system is

$$W = \rho_1 A x + \rho_0 A x_0 + K_2\left\{\left[p_0{}^B + \frac{A}{CC_p}\int_0^{t_1}\frac{q(x,t)}{M(t)}dt\right]^{1/B} - p_0\right\} + K_2\Delta p + \frac{A}{L}\int_{t_2}^{t_1} q(x,t)\,dt + W_H \tag{3}$$

The ideal vent initiation time occurs when the pressure at which the tank structural weight penalty, associated with the pressure increase caused by the heat stored in the propellant, is equal to the propellant mass conserved by storing the heat in the liquid rather than allowing the propellant to boil off. After this optimum pressure is reached, the propellant should be allowed to boil off. The optimum vent time occurs at a point $dW_T/dp = dM_0/dp$.

The mass conserved by storing the heat in the bulk of the propellant is,

$$dM_0 = dQ/L = M(t)C_p dT/L \tag{4}$$

Making the appropriate substitutions,

$$\frac{dM_0}{dp} = \frac{M(t)C_p BC^{1/B}}{L}\left[T_0 + \frac{A}{C_p}\int_0^{t_1}\frac{q(x,t)}{M(t)}dt\right]^{(B-1)/B} \tag{5}$$

The optimum system is represented by $dW/dx = 0$ which can be obtained by differentiating Eq. (3). The resulting equation must be solved simultaneously with Eq. (5) to obtain the values

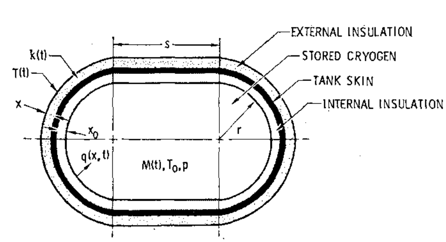

Fig. 1 Cryogenic storage system.

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of x and t at the optimum conditions. The quantity dM_0/dp can be obtained from structural considerations (from the fact that $dM_0/dp = dW_T/dp$) depending upon the shape, size, and the allowable design stress of the storage tank.

The majority of storage systems can be represented by a cylindrical tank with hemispherical ends (Fig. 1), with the ratio of the cylindrical segment height to the radius of the tank ($F = s/r$) defined by the design requirements of a particular storage system.

The tank weight can then be expressed as

$$W_T = (2\pi + 2F\pi)\frac{p\rho}{\sigma}\frac{V}{(4/3)\pi + \pi F}, \text{ or } \frac{dW_T}{dp} = \frac{6(1+F)}{4+3F}\frac{V\rho}{\sigma} \quad (6)$$

The dependence of dW_T/dp on the shape of the tank can be included in the solution of Eq. (5) by substituting Eq. (6).

To illustrate the optimization procedure, a hydrogen tank and an oxygen tank of a reusable space shuttle were analyzed. The analysis was simplified by disregarding the heat stored in the insulation system and tank wall which allowed the following propellant heating approximation

$$q(x,t) = [k_1(t)/x][T(t) - T_0] \quad (7)$$

Substituting Eq. (7) into Eq. (3) and differentiating,

$$\frac{dW}{dx} = \rho_1 A + R\rho_0 A - \frac{K_2}{B} \times \left[p_0{}^B + \frac{A}{CC_p x}\int_0^{t_1}\frac{k_1(t)[T(t) - T_0]}{M(t)}\,dt\right]^{(1/B)-1} \times \left[\frac{A}{CC_p x^2}\int_0^{t_1}\frac{k_1(t)[T(t)-T_0]}{M(t)}\,dt\right] - \frac{A}{Lx^2}\int_{t_1}^{t_2} k_1(t)[T(t) - T_0]\,dt \quad (8)$$

Substituting Eq. (7) into Eq. (5) and solving for x,

$$x = \frac{\dfrac{A}{C_p}\displaystyle\int_0^{t_1}\frac{k_1(t)[T(t)-T_0]}{M(t)}\,\mathrm{dt}}{\left\{\dfrac{dW_T}{dp}\left[\dfrac{L}{M(t)C_pBC^{1/B}}\right]\right\}^{\frac{B}{B-1}} - T_0} \quad (9)$$

Equations (8) and (9) were solved numerically for x and t, to obtain the optimum insulation thickness and time of venting initiation. The constant C was calculated to be 21.9 and 110.0 for hydrogen and oxygen, respectively. The constant B was calculated to be 0.189 and 0.154 for hydrogen and oxygen, respectively. The significant design parameters of the shuttle tanks are shown in Table 1. The hydrogen tank was designed to store liquid hydrogen through the orbital coast phase. Liquid hydrogen required for re-entry was assumed to be stored in a separate tank. The oxygen tank was designed to store liquid oxygen through the re-entry and cruiseback phases. The shape of the hydrogen tank was allowed to vary by varying the parameter F. A spherical oxygen tank was assumed.

The mass history of the hydrogen tank is shown in Fig. 2. A helium purged hydrogen tank insulation during the ground hold period was considered. The high performance insulation was assumed to maintain the ground-hold purge gas thermal conductivity for t_v hours after lift-off. The time t_v was varied parametrically from 0.25 to 2.0 hr. Equations (8) and (9) were solved numerically to obtain the optimum insulation thickness and the time of venting initiation. Sample calculations were selected to illustrate the effect on the optimization process of both the tank geometry and the allowable design stress.

The optimum design pressure was calculated for a hydrogen tank of a constant height to radius ratio representing a typical shuttle configuration. The structural allowable design stress and the insulation vent time were varied to illustrate the effect of these parameters on the optimum design pressure. Results of the analysis are shown in Fig. 3. As shown by the results, any deviation from the nominal 43,000 psi allowable stress would affect the optimum design pressure.

The optimum design pressure was also calculated for a constant volume, constant allowable stress, and variable tank geometry. The chosen volume was a typical shuttle volume. The tank geometry was allowed to vary from a spherical tank ($F = 0$) to a highly elongated tank ($F = 6.0$). The results of the analysis are shown in Fig. 4. As shown by the results, the optimum design pressure is a strong function of both the tank geometry and the insulation vent time. The shape of the pressure curve depends upon the time of the tank venting initiation, changing in shape at the 25 hr point. This change in the curve shape results from the change in the total hydrogen mass which occurs at that time. Hence, the propellant mass history is a significant parameter that affects the optimum tank design pressure.

The optimum insulation thickness for a constant geometry tank is shown in Fig. 3. The optimum insulation thickness for a tank vented through the entire mission with no bulk heat

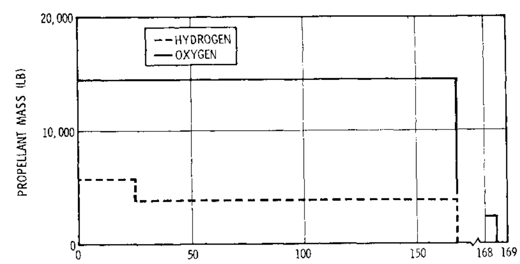

Fig. 2 Orbital maneuvering system propellant mass history.

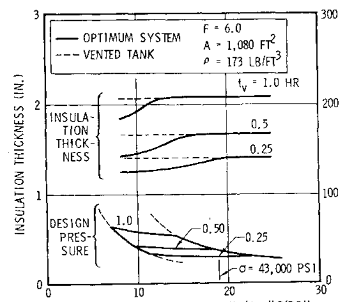

Fig. 3 Optimum hydrogen tank insulation thickness and design pressure.

Table 1 Pertinent space shuttle design parameters

Parameter	Hydrogen tank	Oxygen tank
Tank volume, ft^3	2,300	290
External surface temperature, °F	0	0
Allowable skin stress, psi	43,000	43,000
Re-entry time, min	Not applicable LH_2 stored in separate tank	30.0
HPI thermal conductivity, Btu/hr-ft-°F	10^{-4}	10^{-4}
HPI density, lb/ft^3	5.0	5.0
Mission duration, days	7.0	7.0

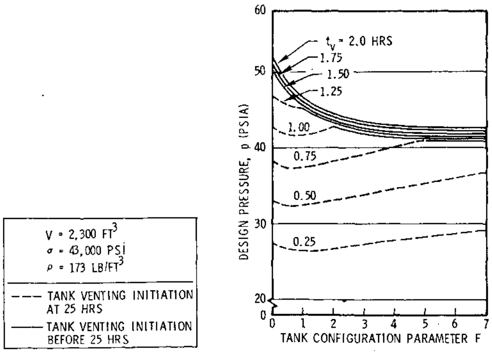

Fig. 4 Configuration effect on the optimum hydrogen tank design pressure.

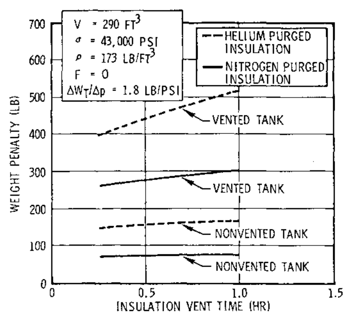

Fig. 5 Total oxygen tank weight penalty.

storage were also calculated and the results are shown in Fig. 3. The thicknesses for the two cases practically coincide since the optimum tank design pressure is very close to the assumed initial tank saturation pressure (approximately 14.7 psia). Therefore, a tank which is vented at 14.7 psia is very close to an optimum design for the chosen tank geometry and allowable design stress.

The mass history of the oxygen tank is shown in Fig. 2. Two insulation systems were considered for the oxygen tank, 1) a nitrogen purged, nitrogen backfilled system and 2) a helium purged, helium backfilled system. Results of analysis indicate that the oxygen tank should not be vented during the entire mission and all of the heat input into the tank should be stored in the bulk of the liquid. The weight penalties associated with the systems considered are shown in Fig. 5, indicating a substantial weight advantage of the nonvented tank over the vented one.

The analysis indicates that both structural and thermal parameters must be considered in designing a minimum weight cryogenic storage system. In an optimum system both heat storage in the bulk of the propellant and propellant boiloff must be utilized to accommodate the heat input into the propellant. The ratio of the heat stored in the bulk of the propellant to the heat allowed to boil off propellant depends on the mission thermal environment, insulation thermal conductivity, propellant mass, type of propellant, and the propellant tank structural weight penalty imposed by designing a system to a pressure above some minimum pressure necessitated by heat storage in the bulk of the propellant. The frequently used process of minimizing a storage system weight considering only an insulation thickness and boiled off propellant as pertinent parameters is often inadequate.

120-In. Large Space Telescope (LST)

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Introduction

THE need for continuation and expansion of present programs in space astronomy, has been recognized by the scientific community.[1-3] For example, atmospheric distortion limits the resolving capability of the Hale 200-in. telescope at Palomar to that of a 12-in. telescope in orbit.

The Large Space Telescope (LST) program called for by the scientific community is now formally included as a line item in the NASA/OSSA budget. The discoveries possible with this instrument's 10-ft-diam aperture of diffraction limited performance will dwarf the discoveries of all previous instruments.

Mission

A viable LST observation program must last at least 10 yr with no more than two flight vehicles. Each vehicle must have the capability to function as an international observatory, in much the same manner as the Palomar terrestrial observatory. In addition, a variety of experimental packages must be available for use with the same collecting optics. The experiments should be conceived and guided by a cross section of the astronomical community as principal investigators. The utility of these experiments can be further extended by the participation of guest investigators as now successfully practiced on OAO-2.

A Baseline LST Configuration

The LST configuration presented in Fig. 1, while not optimized, is a reasonable approach toward meeting mission objectives. This configuration has primarily been used as a baseline to analyze systems and subsystems, identify major trade areas, and form a springboard toward realization of an optimized design. Major subsystems including stabilization and control (S&C), communications and data handling (CDH), electrical power, and the pneumatics are packaged as separate modules capable of replacement in orbit via the space shuttle. They are located at the spacecraft (or rear) end of the configuration.

Forward of the spacecraft structure is the "reference base," a specially stabilized structure to relate all geometrically critical components on the vehicle. The fine-error sensor of the S&C system is located on the axis of the reference base. This sensor is the innermost loop of the concentric or nested S&C modes but not contained in the S&C module. The experiments are radially disposed in the reference base. They are independent and modularly packaged and removable externally. The reference base also supports the telescope, precisely relating it to the experiments and fine-error sensor, via the primary and secondary mirror support structures.

The aft end of the spacecraft structure is fitted with a docking adapter. The docking ring has a central opening through which the fine-error sensor package can be replaced. All modules can be replaced by manipulator arms which are part of the shuttle deployment mechanism.

This independent experiment module configuration permits great flexibility in payload (experiment) complement: experiments may be replaced in orbit permitting updating through

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