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TECHNOLOGY REPORT

ECONOMIC ANALYSIS OF PERLITE VERSUS SUPER INSULATION IN LIQUID HYDROGEN STORAGE AND RUN VESSELS FOR THE M-1 PROGRAM

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ABSTRACT

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This report is an evaluation, on a cost comparison basis, of the economic aspects of two possible insulation systems, powder type (Perlite) and multilayer aluminum foil reflective type (Quilted Super Insulation). The analysis applies to 370,000 and 575,000 gallon liquid hydrogen storage dewars rated at 50 and 100 psig designed for the M-1 Engine Program.

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I. SUMMARY

The economic aspects of two possible insulation systems for large volume liquid hydrogen storage dewars for the M-1 Engine Program are evaluated, on a cost comparison basis, in this report. This evaluation of Perlite versus Quilted Super-Insulation (QSI)* also includes technical data where applicable to cost/effectiveness decisions.

A. OPERATIONAL COST SAVINGS IN LIQUID HYDROGEN FIRST COST DIFFERENTIAL BETWEEN PERLITE AND QSI

For large storage dewars, the operational savings associated with the use of QSI over a five year period proved to be significant when compared with the greater first cost of QSI; therefore, the procurement of QSI appears to be warranted. For large run vessels, where more frequent childown cycles are anticipated, operational savings increase significantly with the use of QSI insulation.

B. TECHNICAL EVALUATION OF PERLITE vs. QSI

In the technical sense, both Perlite and QSI are adequate types of insulation for vessels which are not subject to frequent warm-up and childown cycles or to mechanically-induced or sonically-induced vibrations. Where these conditions exist, QSI exhibits definite advantages over Perlite.

C. INTANGIBLE OPERATIONAL COMPARISON OF PERLITE vs QSI

From the maintenance aspect, QSI appears superior to Perlite because a QSI-insulated vessel will maintain vacuum in the annular space for a longer period of time than will Perlite. In addition, the annular space in a QSI-insulated vessel is accessible without removing the insulation to accomplish system repairs, whereas this is not the case with Perlite-insulated vessels.

Based upon qualitative analysis, Perlite appears to be superior to QSI from the aspect of resistance to damage to the inner vessel from shock or shrapnel. A quantitative analysis to determine the extent of this superiority would require design information concerning the vessel support structure and a testing program to determine the actual effectiveness of Perlite as a shock absorber.

II. INTRODUCTION

Testing requirements for the M-1 engine dictated the need for large capacity propellant storage and run vessels. Proper insulation of these vessels is a major factor in keeping propellant boil-off losses to a minimum.

The purpose of this study is twofold: documentation of all available information applicable to a cost evaluation of Perlite versus Super-Insulation as

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*QSI is a tradename of the Linde Corporation related to large volume liquid hydrogen storage and run dewars; and to make recommendations as to a course of action with regard to the type of insulation to be specified in the procurement of liquid hydrogen storage and run vessels. These recommendations to be the result of fixed costs as well as anticipated operational costs.

The preponderance of experience is with the large dewars containing Perlite insulation. Thus, the major question is whether the more sophisticated multilayer reflective type of insulation can provide measurable reductions in operating expenses in sufficient value to offset its high initial cost of installation. The answer to this question involves such factors as:

1. Direct Cost

2. Operating costs resulting from the normal daily losses of liquid hydrogen.

3. Operating costs resulting from losses during initial cooldown and subsequent cycles of warm-up and cooldown of the equipment.

4. Whether decompaction or reconditioning of the Perlite will be required after a nominal number of cooldown cycles.

5. Facility time losses attributable to the duration of facility cooldown or warm-up.

6. The advantages or disadvantages of Perlite in the annular space as a shock absorber to provide protection for the inner shell from impact loads caused by the impingement of shrapnel or explosive over-pressure shock waves on the outer shell.

Two facilities were considered in this comparative analysis. The first is a 370,000 gallon liquid hydrogen storage vessel with operating pressures of 50 psig or 100 psig. The second is a run vessel of 575,000 gallons which will operate at 100 psig. These are typical of the vessels intended for M-1 Engine Program procurement.

Analysis of the study results permit conclusions to be made relevant to the following major considerations:

The cost savings in liquid hydrogen losses justifying the greater initial cost of installing Super-Insulation rather than Perlite for vacuum-jacketed storage and run vessels.

The technical advantages of Super-Insulation as compared with Perlite.

The intangible operational considerations that should be taken into consideration when using either Super-Insulation or Perlite.

III. TECHNICAL DISCUSSION

A. ASSUMPTIONS

The following basic assumptions were made in the development of calculations applicable to the economic and technical evaluation of Perlite versus QSI for insulation of large volume liquid hydrogen storage and run vessels. These assumptions are delineated in the ensuing discussions.

1. Liquid Hydrogen Cost

Liquid hydrogen was assumed to cost $ 0.60/lb delivered to the Sacramento Liquid Rocket Operations. To a great extent, this cost depends upon the production capability of west coast liquid hydrogen plants as well as upon the usage rate. The current price of liquid hydrogen delivered to Sacramento is $ 0.80/lb; however, it appears that a price of $ 0.60/lb is realistic for the duration of the M-1 Engine Program. Should a cost comparison using some other price per pound be desired, it can be obtained by multiplying the cost data presented herein by the appropriate ratio.

2. Steady-State Boil-Off

Vessel configuration and insulation thickness were derived from calculations based upon the following steady-state boil-off conditions:

a. Conductive heat leak through steel - .02% loss/24 hours

b. Conductive and radiation heat leak through insulation - .03% loss/24 hours

c. Total heat leak - .05% loss/24 hours

Consultations with the manufacturers of vacuum-insulated vessels and independent AETRON calculations support the vessel configuration and insulation thickness used in this study. It was determined that 5-ft. of Perlite was equivalent to approximately 6.4-in. of QSI with respect to steady-state conductivity and radiation heat gain through the insulation. The 3-ft. annular space allowance for the QSI-insulated vessel was based upon fabrication and installation requirements. QSI has been installed in a 100,000 gallon cylindrical vessel with only 2-ft. annular space allowance between inner and outer shells; however, it appears that a minimum clearance of 3-ft. would be required in the case of a spherical vessel to permit high quality installation of the QSI.

Additional information regarding actual boil-off losses is also available.*

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* Liebenberg, D. H., Stokes, R. W., and Edeskuty, F. J., Childown and Storage Losses of Large Liquid Hydrogen Storage Dewars, Paper presented to the Cryo-Genic Engineering Conference at Rice University, Houston, Texas, August 1965

3. Comparison Items

To provide a valid economic comparison, Perlite-insulated and QSI-insulated vessels were compared based upon total liquid hydrogen usage for each cooldown cycle. Transfer operation losses vary depending upon the total quantity of liquid hydrogen transferred through the system and this varies with the type of insulation used. Therefore, all operational losses have been considered in determining the amount of liquid hydrogen required to effect system chilldown as well as transfer and filling of the vessel to the 90% level.

An objective comparison between Perlite and QSI necessitates heat leak studies based upon the total vessel operating system. The optimum storage vessel system must deliver the maximum useful pounds of liquid hydrogen from the tank car receiving connection to the operating run tank at the least cost.

The 370,000 gallon storage vessel system cooldown loss, its steady-state loss, the shipment trailer pressurization loss during unloading, and the friction loss while pumping are all part of the total system liquid hydrogen useage per operating cycle. These liquid hydrogen requirements for the 370,000 gallon storage vessels are presented in Tables 1 and 2 relative to operating transfer pressure. Table 3 presents the liquid hydrogen requirements for the 575,000 gallon run vessel. The liquid hydrogen losses associated with these operations are relative to vessel loading and transfer pressures.

Two operating pressure levels of 50 psig and 100 psig have been evaluated for the 370,000 gallon storage vessel system and comparative costs are shown in Tables 4 and 5. Table 6 presents costs for the 100 psig, 575,000 gallon LH_2 run vessel. The cost of QSI and the comparative amounts of liquid hydrogen required for cooldown are shown in Figures 1, 2, and 3. It should be noted that the vessel insulated with QSI reaches steady-state boiloff conditions in significantly less time than the vessel insulated with Perlite.

4. Heat Transfer Coefficients

The Perlite heat transfer coefficient, k, was assumed to be 78.5×10^{-5} BTU-ft/hr-ft^2-°F, although some vessel manufacturers claim that heat transfer coefficient values as low as 58×10^{-5} can be achieved at liquid hydrogen temperatures. The QSI heat transfer coefficient, k, was selected as 10×10^{-5} BTU-ft/hr-ft^2-°F.

A thermal conductivity comparison between Perlite and QSI was made. The thermal conductivities of Perlite and QSI vary with absolute pressure. Five feet of Perlite at 25 microns pressure appears to be equivalent to 6.4-in. of QSI operating at 0.1 micron pressure. The heat transfer coefficient for Perlite changes with density and the level of vacuum as shown in Figures 4 and 5. The cross-hatched area on Figure 5 indicates the probable k values for Perlite under conditions resulting from cryo-pumping. For the purposes of this study, the k value used was 78.5×10^{-5} BTU/hr-ft^2-°F/ft. The related pump-down curves for Perlite are shown on Figure 6.

FILLING LIQUID HYDROGEN VESSEL; 370,000 GALLONS (50 psig)

TRANSFER OPERATIONS	LIQUID HYDROGEN USAGE - LBS @ 50 PSIG	
	PERLITE	Q S I
1. Line Cooldown	565	565
2. Line Evaporation Losses	225	195
3. Line Friction Loss	1,640	1,460
4. Liquid Residue in Line	130	130
5. Inner Vessel Cooldown	38,000	38,000
6. Insulation Cooldown (during Fill Period)	27,900 (54,700 Total)	5,350
7. Vessel Evaporation Loss*	120	105
8. Vessel Fill 90%	196,500	196,500
9. Trailer Pressurization	3,015	2,720
10. Total LH_2 Requirement**	268,095#	245,025#
11. Ratio of LH_2 Delivered On-Site to LH_2 Arrival in Storage	1.37	1.25
12. Cooldown Pumping Time, Hrs.	3.5 - 4	3.5 - 4
13. LH_2 Flow Time, Hrs.	12.4	11.3
14. Total Connected Time, Hrs.	21.6	19.8
15. Number of 13,000 Gallon LH_2 Trailer Loads	34.0	31.0

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* Denotes evaporation loss during period of fill cycle. Based on vessel being in service 11 months out of the year. The total yearly evaporation loss = 79,500#

** Pounds of LH_2 required to cooldown and fill 370,000 gallon vessel; one time.

TABLE 1

TABLE 2

FILLING LIQUID HYDROGEN VESSELS; 370,000 GALLONS (100 psig)

TRANSFER OPERATION	LIQUID HYDROGEN USAGE - LBS @ 100 PSIG PERLITE		LIQUID HYDROGEN USAGE - LBS @ 100 PSIG Q S I
1. Line Cooldown	565		565
2. Line Evaporation Losses	220		195
3. Line Friction Losses	1,640		1,460
4. Liquid Residue in Line	130		130
5. Inner Vessel Cooldown	62,000		62,000
6. Insulation Cooldown (During Fill Period)	27,900	(54,700 total)	5,350
7. Vessel Evaporation Loss *	120		105
8. Vessel Fill 90%	196,500		196,500
9. Trailer Pressurization	3,015		2,720
10. Total LH_2 Requirement **	292,090		269,025
11. Ratio of LH_2 Delivered On-Site to LH_2 Arrival in Storage	1.49		1.37
12. Cooldown Pumping Time, Hrs.	5 - 6		5 - 6
13. Fill Pumping Time, Hrs.	13.8		12.7
14. Total Connected Time, Hrs.	24.0		22.0
15. Number of 13,000 Gal. LH_2 Transfer Loads	38.0		35.0

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* Denotes evaporation loss during period of fill cycle. Based on vessel being in service 11 months out of the year. The total yearly evaporation loss = 79,500#.

** Pounds of LH_2 required to cooldown and fill 370,000 gallon vessel; one time.

TABLE 3

FILLING LIQUID HYDROGEN RUN VESSEL; 575,000 GALLONS (100 psig)

TRANSFER OPERATION	LIQUID HYDROGEN USAGE - LBS @ 100 PSIG	
	PERLITE	Q S I
1. Line Cooldown	3,930	3,930
2. Line Evaporation Losses	605	555
3. Line Friction Losses	4,475	4,130
4. Liquid Residue in Line	1,925	1,925
5. Inner Vessel Cooldown	89,100	89,100
6. Insulation Cooldown (During Fill Period)	37,500 (74,000 Total)	7,310
7. Vessel Evaporation Loss *	150	140
8. Vessel Fill 90%	305,000	305,000
9. Pressurization Gas Loss	13,500	12,350
10. Total LH_2 Requirement **	456,185	424,440
11. Hours to Transfer	13	12
12. Sources of LH_2 Transfer to 575,000 gal. Run Vessel		
VK-1-LH_2 Storage, 3900 ft. Transfer Distance	196,500	196,500
VK-2-LH_2 Storage, 3100 ft. Transfer Distance	196,500	196,500
VK-17-LH_2 Storage, 3450 ft. Transfer Distance	55,060	23,940
VK-10-LH_2 Storage Converted to Gas	8,125	7,500
13. Cooldown Time (Fast)	3 - 4 Hrs.	3 - 4 Hrs.

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* Denotes evaporation loss during period of fill cycle. Based on vessel being in service 10 months out of the year. The total yearly evaporation loss = 83,200#.

** Pounds of LH_2 required to cooldown and fill 575,000 gallon vessel; one time.

TABLE 4

LIQUID HYDROGEN STORAGE VESSEL COMPARATIVE COSTS
370,000 gallons at 50 psig
5-Year Operating Life

ITEM			PERLITE COSTS $	Q S I COSTS $
A.	INSULATION			
	1.	5-Foot Perlite	16,400	
	2.	6.4 Inches QSI		95,000
B.	VESSEL			
	1.	55' -8 3/4" I.D. with Perlite	366,000	
	2.	51' -8 3/4" I.D. with QSI		332,000
C.	INITIAL INVESTMENT		382,400	427,000
D.	OPERATIONS PROCUREMENT; 5-YEARS			
	1.	Steady-State Boiloff* (Steel and Insulation Heat Leak)	126,000	126,000
	2.	Decompaction; 1 Time	15,000	
	3.	Insulation Childown @ 1 Cycle Per Year	164,100	16,100
	4.	Sub-Total**	305,100	142,100
E.	TOTAL COSTS		687,500	569,100
F.	SAVINGS IN 5-YEARS			118,400

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* $126,000 is based upon 0.021% boiloff caused by heat leak through steel and 0.03% boiloff due to heat leak through insulation.

** Hydrogen Costs at $0.60 per pound

TABLE 5

LIQUID HYDROGEN STORAGE VESSEL COMPARATIVE COSTS

370,000 gallons at 100 psig
5-Year Operating Life

ITEM			PERLITE COSTS $	Q S I COSTS $
A.	INSULATION			
	1.	5-Foot Perlite	16,400	
	2.	6.4 Inches QSI		95,000
B.	VESSEL			
	1.	55' - 8 3/4" I.D. add Perlite	472,000	
	2.	51' - 8 3/4" I.D. add QSI		438,000
C.	INITIAL INVESTMENT SUB-TOTAL		488,400*	533,000**
D.	OPERATIONS PROCUREMENT; 5-YEARS			
	1.	Steady-State Boiloff* (Steel & Insulation Heat Leak)	126,000	126,000
	2.	Decompaction @ 1 Time	15,000	
	3.	Insulation Childown @ 1 Cycle Per Year	164,100	16,100
	4.	Sub-Total	305,100	142,100
E.	TOTAL COSTS		793,500	675,100
F.	SAVINGS IN 5-YEARS			118,400

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* CB&I Estimate $470,000 vs.
** CB&I Estimate $579,000 vs.

TABLE 6

LIQUID HYDROGEN RUN VESSEL COMPARATIVE COSTS
575,000 gallons at 100 psig
5-Year Operating Life

ITEM		PERLITE COSTS $	Q S I COSTS $
A.	INSULATION		
	1. 5-Foot Perlite	22,800	
	2. 6.4 Inches QSI		116,600
B.	VESSEL		
	1. 63' - 0" I.D. with Perlite	768,000	
	2. 59' - 0" I.D. with QSI		707,000
C.	INITIAL INVESTMENT SUB-TOTAL	790,000**	823,600***
D.	OPERATING PROCUREMENT; 5-YEARS		
	1. Cycled Boiloff*	162,500	162,500
	2. Decompaction, 3-Times	60,000	
	3. Insulation Chilldown* @ 2 Cycles Per Year Based on:		
	a. 529,800 lbs Perlite	440,000	
	b. 5,670 lbs QSI		43,860
	4. Sub-Total	662,500	206,360
E.	TOTAL COSTS	1,452,500	1,029,960
F.	SAVINGS IN 5-YEARS		422,540

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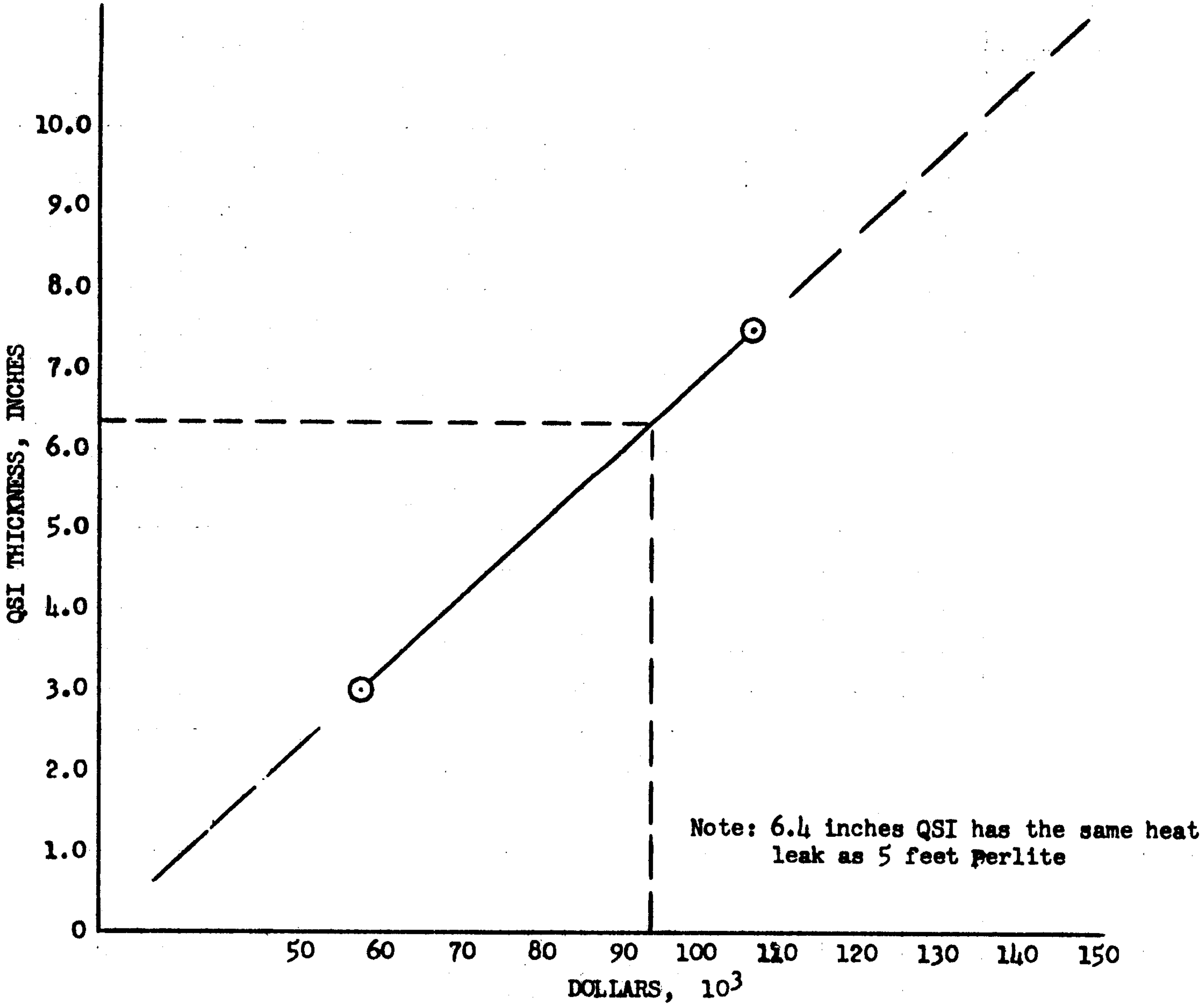
* Hydrogen Costs at $0.60 per pound
** CB&I Estimate $806,000
*** CB&I Estimate $911,000



Note: 6.4 inches QSI has the same heat leak as 5 feet Perlite

FIGURE 1

QSI COSTS FOR 370,000 GALLON STORAGE VESSEL

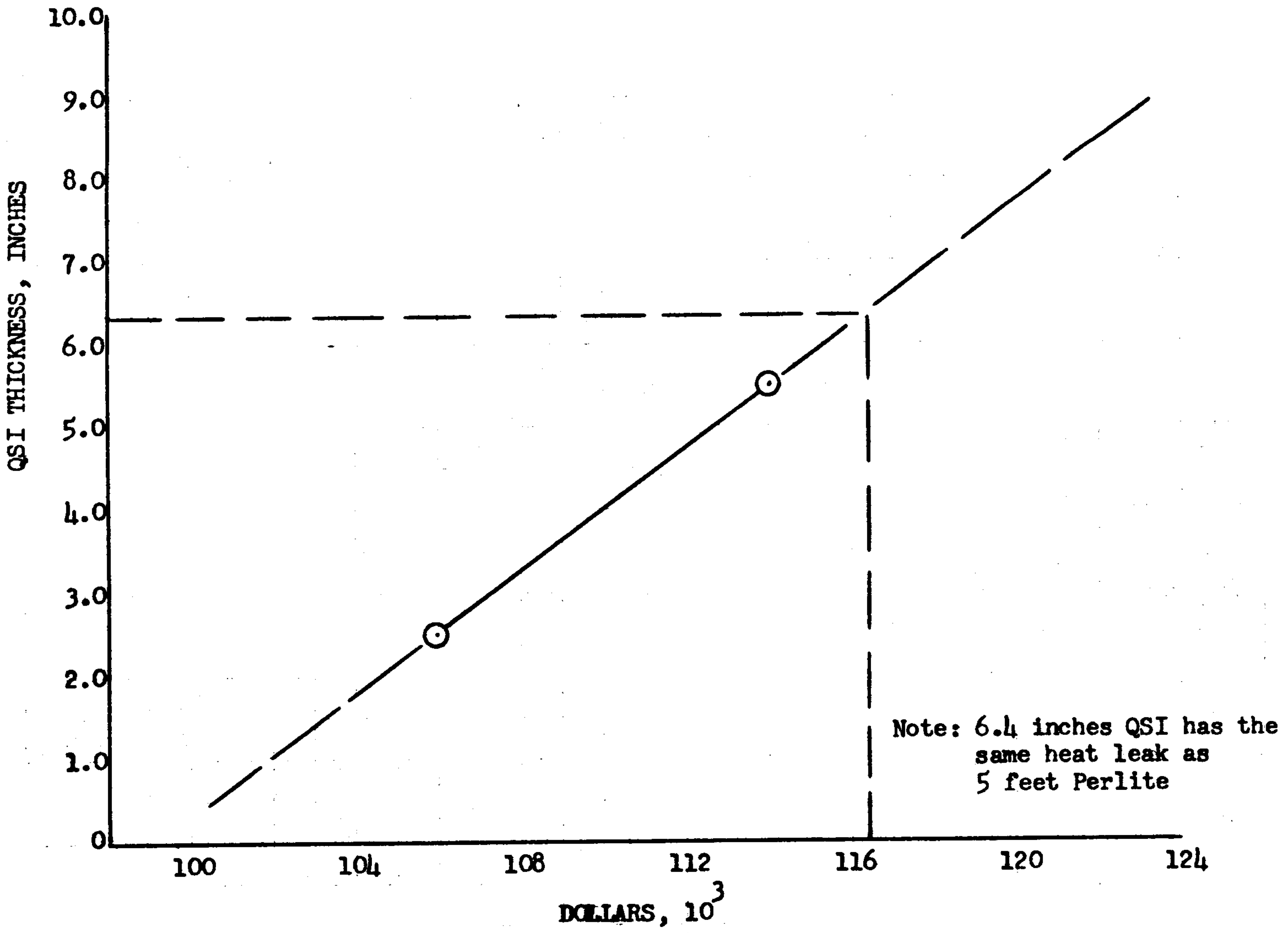


FIGURE 2

QSI COSTS FOR 575,000 GALLON RUN TANK

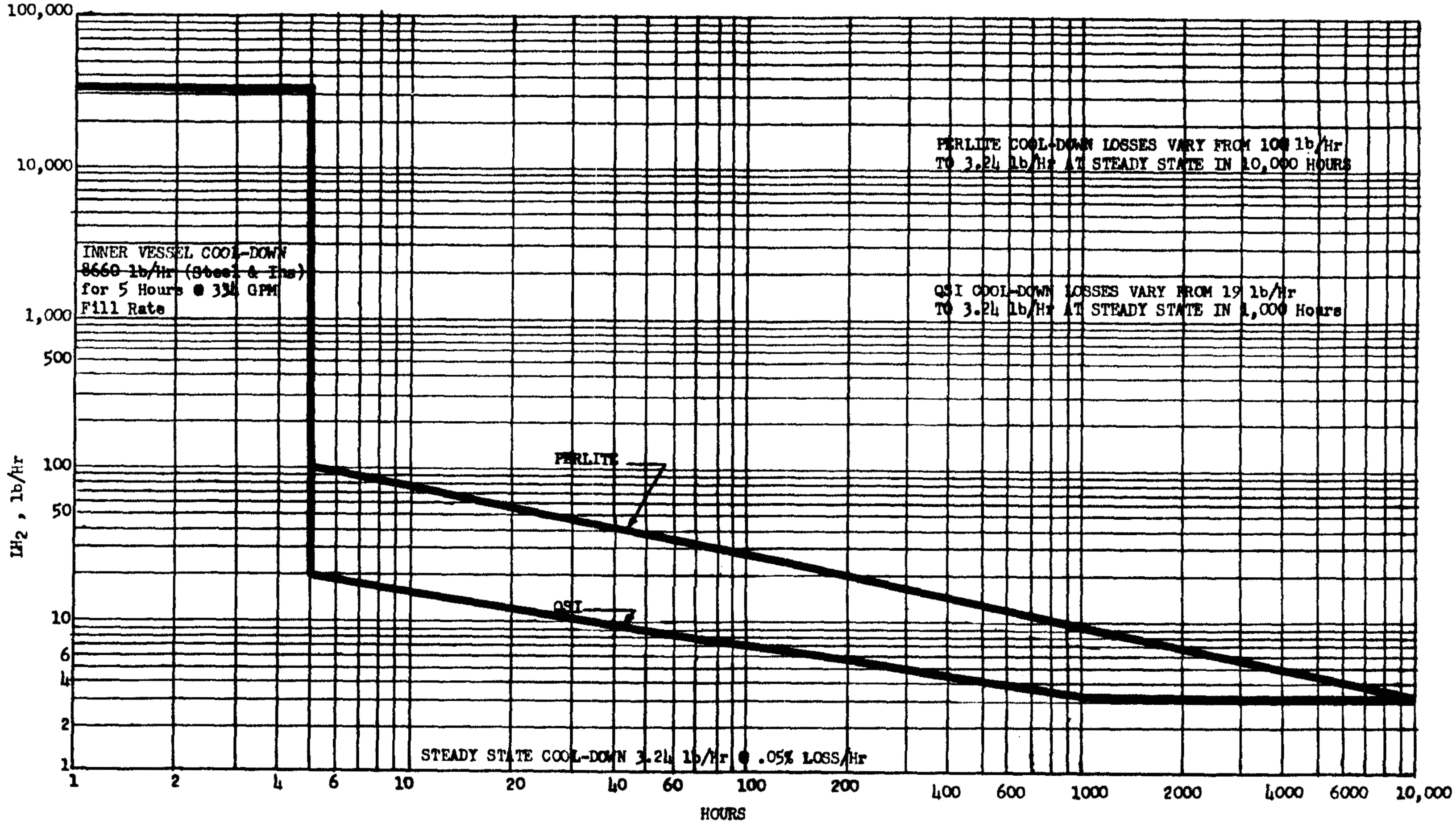


Figure 3. Cooldown and Steady-State Losses for 370,000 Gallon, 50 psi Storage Vessel (Perlite vs QSI)

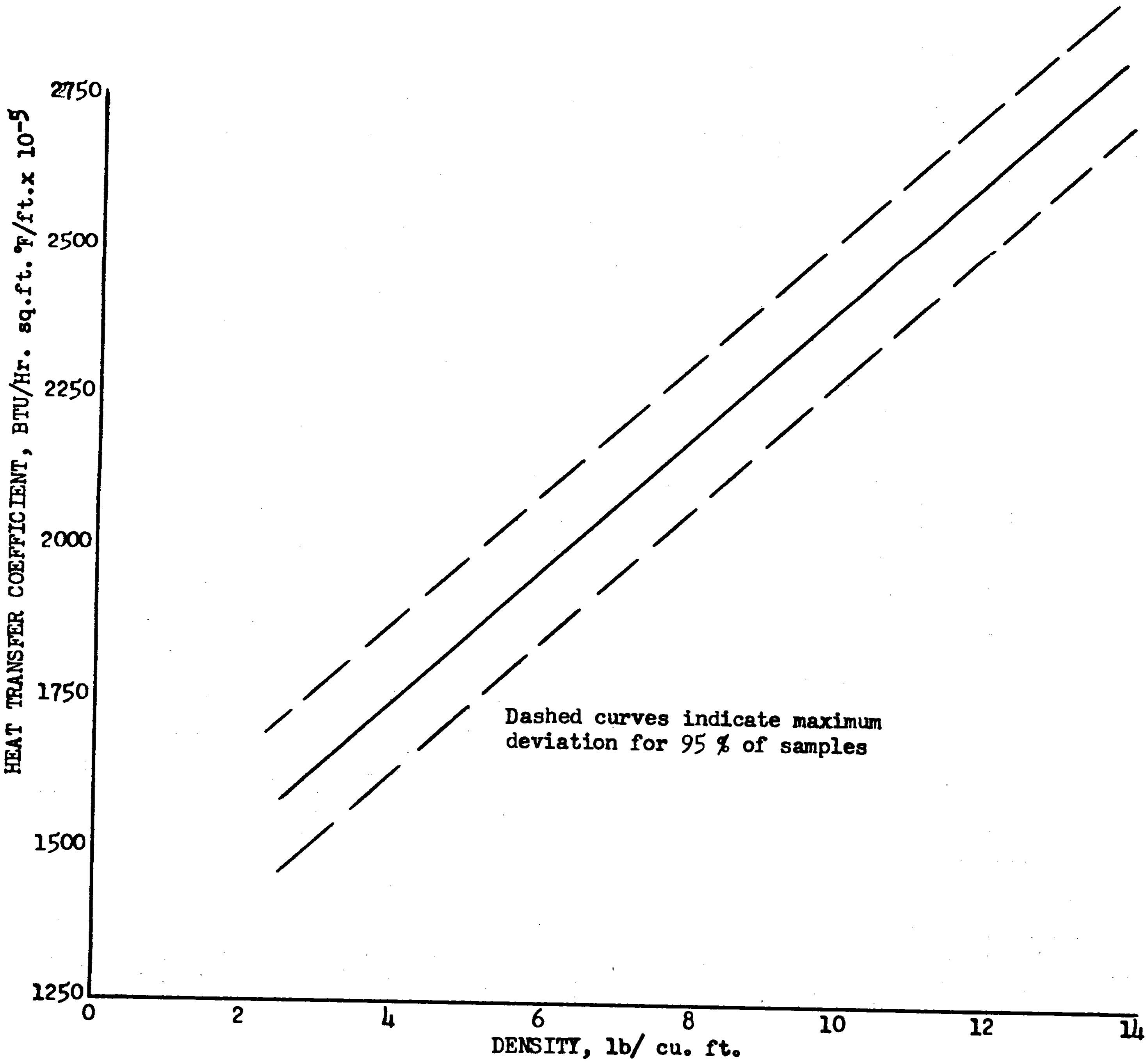
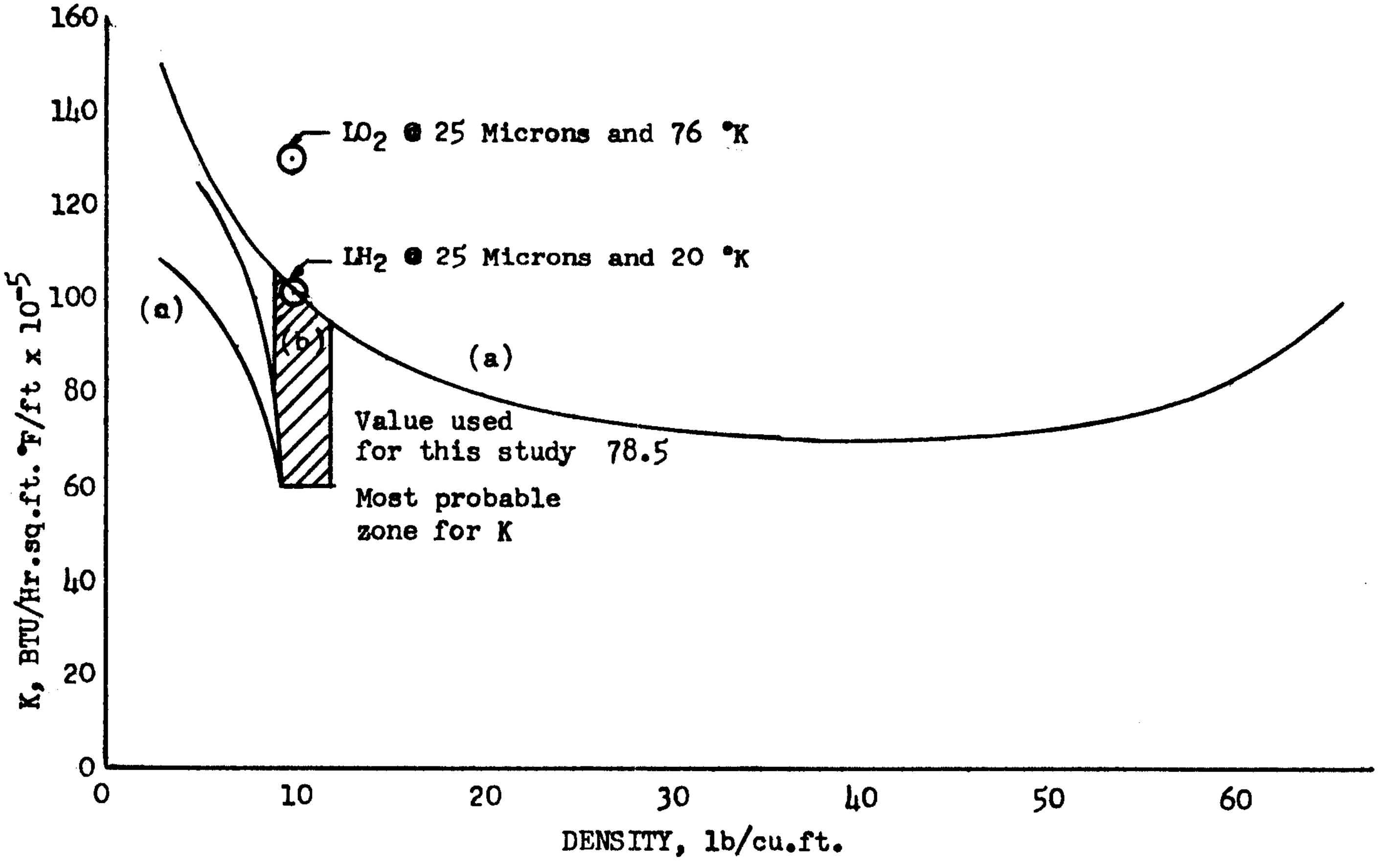


FIGURE 4

HEAT TRANSFER COEFFICIENT OF UNEVACUATED PERLITE VS. DENSITY



(a) Particle size of samples 450 - 150 u. Interstitial gas pressure 10^{-4} Torr. Th = 300°K, Tc = 76°K

(b) Both hot and cold-wall emissivity of 0.86 Th = 300°K, Tc = 76°K

(c) Hot-wall emissivity of 0.86; cold-wall emissivity of 0.02, Th = 300°K, Tc = 76°K

FIGURE 5

k_a VS DENSITY FOR EVACUATED PERLITE

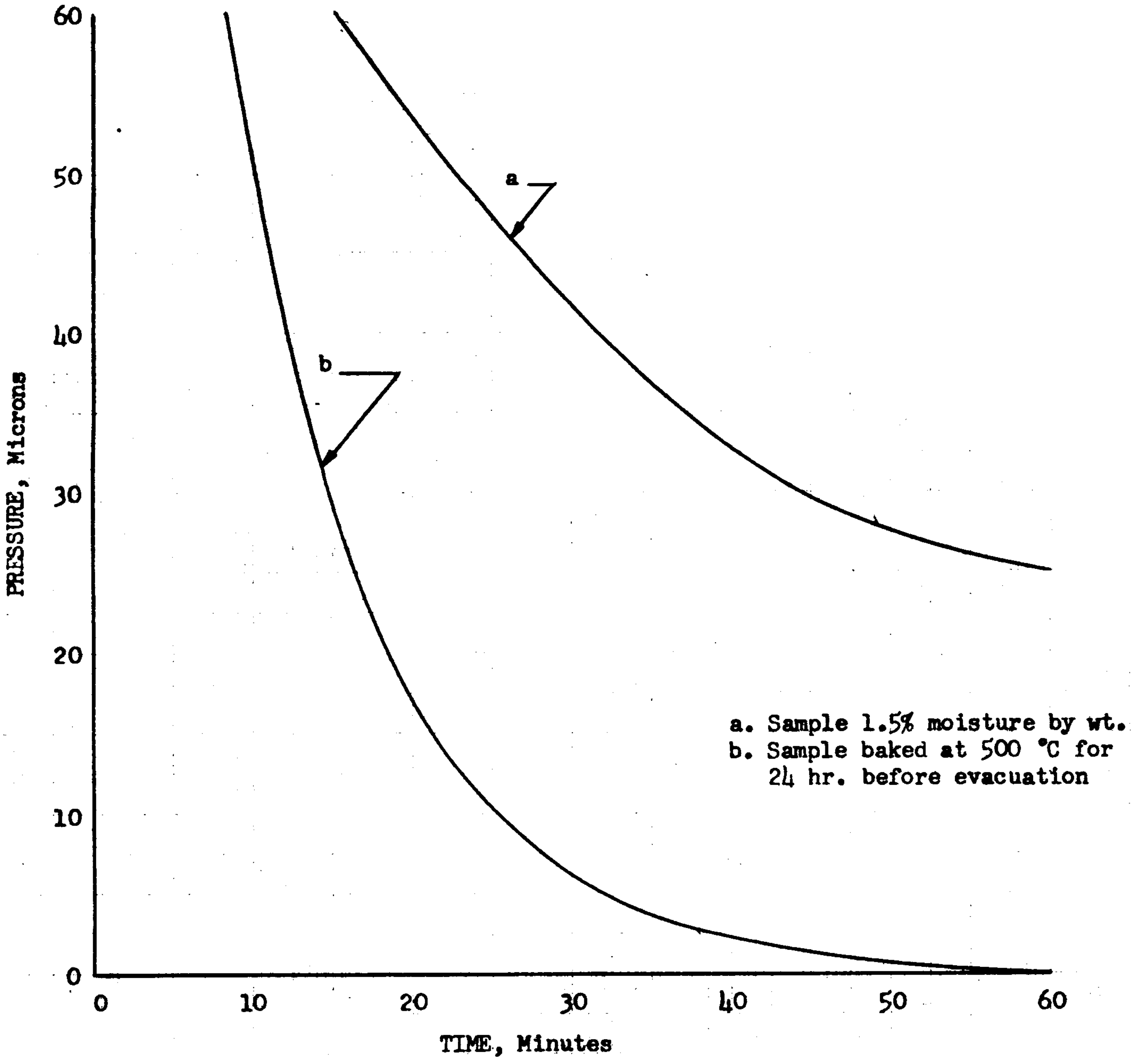


FIGURE 6

PUMP-DOWN CURVES FOR PERLITE

The apparent mean thermal conductivity of the Perlite varies with the external hot wall temperature in accordance with the curve shown on Figure 7. Note that the temperature gradient of the Perlite bed will create changes in the heat transfer coefficient. The most realistic steady-state heat loss value can be derived if k is obtained by log-mean evaluation of the incremental temperature and pressure of the Perlite insulation. The cryogenic pumping effects of the liquid-hydrogen-cooled wall will further decrease pressure by condensing gases, other than helium and hydrogen which are present in the annular volume. The cryopumping and cooling of these gases will reduce a 25 micron pressure to 2.2 micron in the 370,000 gallon storage vessel annulus. The range of thermal conductivities for multi-layer Super-Insulation varies from 5.78×10^{-5} to 1.73×10^{-5} BTU-ft/hr-ft^2-°F. depending upon the material, the density of compaction, the degree of vacuum, and the cold wall temperature. The thermal conductivity of QSI also varies directly with the external hot wall in accordance with the curve shown on Figure 8. Caps between adjacent shields at corners or joints can add significantly to the theoretical total heat transport; therefore, a heat transfer coefficient of 10×10^{-5} BTU-ft/hr-ft^2-°F. was used in the comparison calculations. This is a conservative value and is obtainable by several manufacturers of multi-layer Super-Insulations. This judgment has been confirmed by the Linde Company, manufacturers of QSI, as well as by the National Research Corporation, which claims a capability for installing their insulation (NRC) at an even lower k value.

5. Duration of Operation

Operation life of both storage and run vessel systems was assumed to be five years.

To establish a basis for economic comparison between Perlite and QSI, it was first necessary to establish an operational life for the vessel systems used in the comparison. The storage and run vessels evaluated in this study are for use in the development of the M-1 engine; therefore, the anticipated duration of the M-1 Engine Program was used to determine vessel operational life. The vessels have been assigned a five year operational life which coincides with the period of operation scheduled for K-Zone M-1 engine testing. However, it is not expected that the useful life of the vessels will terminate upon the completion of the M-1 Engine Program.

6. Chilldown Cycles

Insulation chilldown cycles were assumed to occur once a year in the case of storage vessels and twice a year in the case of run vessels.

It was extremely difficult to project the number of cooldown cycles which could be expected each year in the case of liquid hydrogen storage and run vessels associated with engine test programs. Minimal information was gleaned from the liquid hydrogen producers because they seek to avoid the cycling of storage vessels. In correspondence with Linde, Air Products, and other cryogenics manufacturers, it was found that once liquid hydrogen production plants become operational, the storage vessels are left cold indefinitely. Discussions with

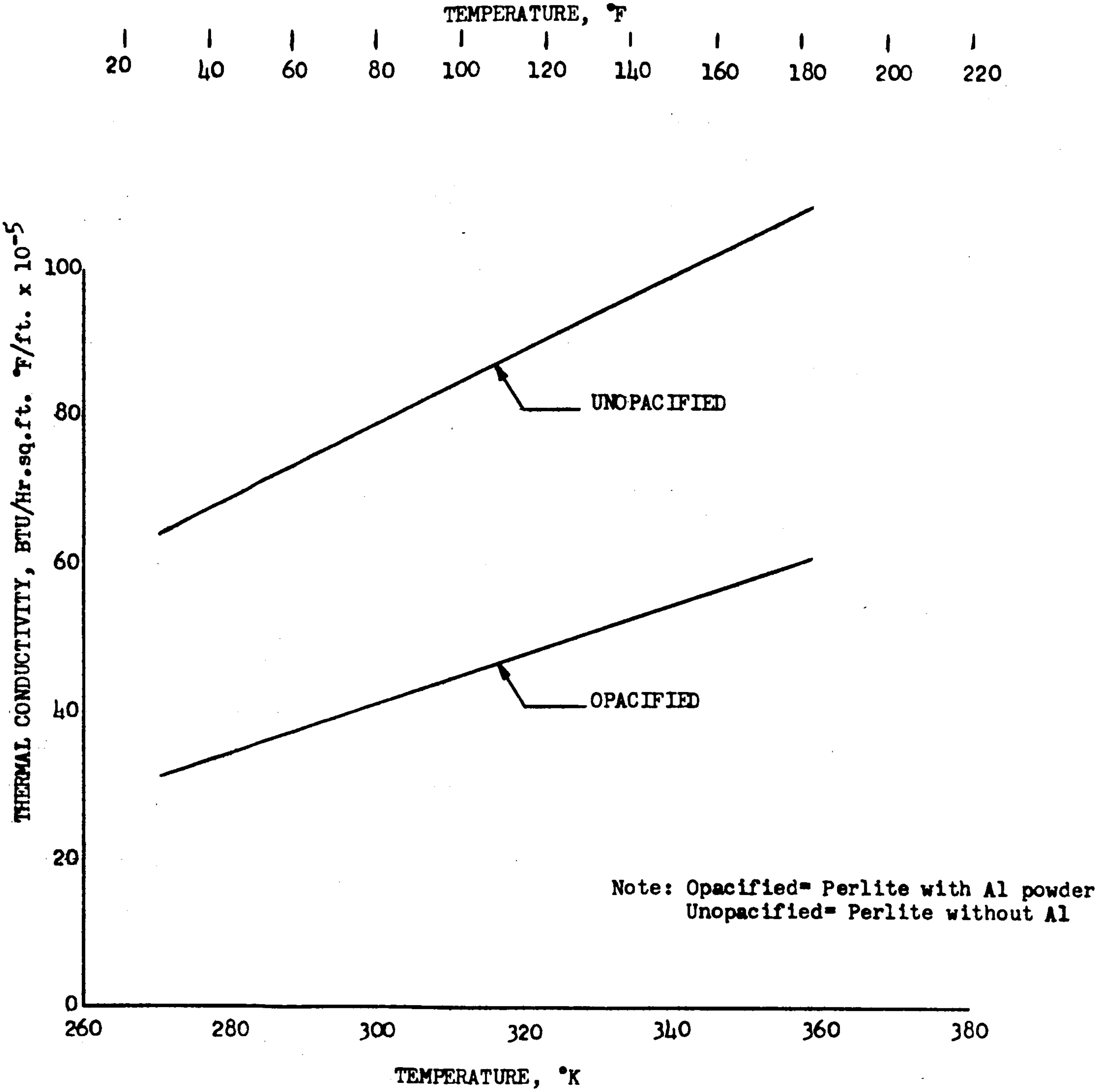


Figure 7. Apparent Mean Thermal Conductivity of Perlite vs Hot Wall Temperature with Cold Wall Held at 76° K

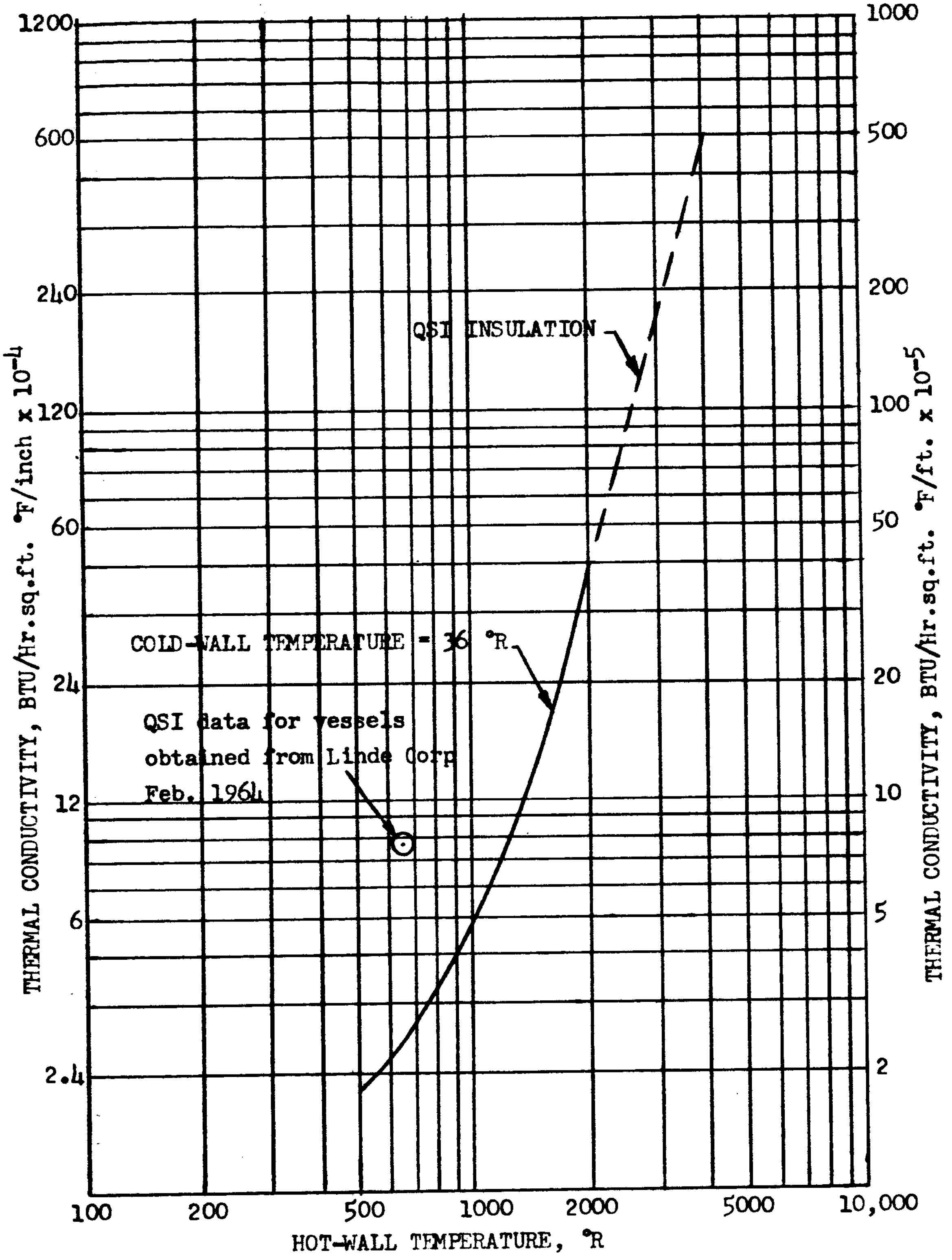


FIGURE 8

THERMAL CONDUCTIVITY OF QSI VS UPPER TEMPERATURE

Rocketdyne facility engineers indicated that the problem of vessel cycling is ignored and no records are kept to indicate the number of cooldown cycles experienced by a vessel although it was stated that operations personnel prefer Super-Insulated vessels to Perlite-insulated vessels.

The assumption used in this study with regard to cycling vessels is based upon the educated engineering judgement of Aerojet-General Liquid Rocket Plant personnel rather than the experience of liquid hydrogen producers or users. It appears feasible to expect that a storage vessel would require warm-up once a year for inspection, repair of equipment, or possible unexpected curtailment of testing. Because run vessels are exposed to damaging test malfunctions, are more affected by modifications resulting from configuration changes in the test hardware, and are subjected to frequent intervals of high as well as low frequency vibrations, it was estimated that a run vessel would most likely be temperature-cycled a minimum of twice a year.

7. Perlite Reconditioning

Reconditioning of Perlite is assumed to be required after every fifth chilldown cycle in the case of storage vessels. For run vessels subject to vibration, decompaction or reconditioning of Perlite is assumed to be required after every third chilldown cycle.

When installing Perlite in vacuum-jacketed vessels, as much material as possible is packed in. It is deliberately compacted so that no further slump or shifting will occur after the vessel is sealed. With this compaction technique, vibration susceptibility, at least for storage vessels, appears to present no problems. However, run vessels are subject to a severer vibration environment and experience a greater number of chill cycles, during which the inner vessel will shrink disproportionately from the outer vessel. Consequently, even though the annulus is initially filled and well compacted, a certain amount of "void" space at the insulation boundary adjacent to the inner vessel may be anticipated and some slump may occur to fill the void. During the following warm-up cycle, this "excess" of insulation which has been packed into the lower portions of the annulus will be obliged to experience further compaction. This results in stresses being imposed upon the inner and outer vessels as well as the various interconnecting ties between them. If continuing slump were to occur during each thermal cycle, the resulting successive, cumulative stresses may cause failure of some portions of the vessel suspension system.

Consultations with liquid hydrogen producers and rocket engine development contractors experienced in handling liquid hydrogen have been inconclusive with regard to Perlite compaction caused by thermal cycling and/or vibration. Most large Perlite-insulated dewars in service have not undergone sufficient temperature cycles to establish reliable empirical data regarding the compaction of Perlite. However, one major manufacturer, Chicago Bridge and Iron, has gone on record to the effect that thermal cycling of the vessel will, in their opinion, cause compression of the Perlite in the lower half of the annular space. This would cause displacement of the inner sphere with respect to the outer sphere with the consequence of overstressing the suspension system and distorting nozzles. They recommend that large spherical liquid hydrogen storage vessels not be thermal cycled more than five times. Further, they have stated that they cannot guarantee the integrity of vessels exposed to a greater number of thermal cycles unless such a requirement is imposed in the original procurement specifications.

Based upon this information, the assumptions presented in the opening paragraph of this Perlite reconditioning discussion are recommended for consideration in the economic evaluation of Perlite versus QSI insulation.

B. CONSIDERATION OF TANGIBLE FACTORS - PERLITE vs. QSI

The following is a summary of the program cost comparisons associated with the use of Perlite versus QSI-insulated vessels.

1. 370,000 Gallon LH_2 Storage Vessel

As shown in Table 4, the 370,000 gallon liquid **hydrogen storage** vessel will show a probable total savings of $118,400 in five years by using QSI, taking into account operational savings and the assured higher erection cost of $44,600 for the QSI-insulated vessel. Operational savings include $15,000 relating to one Perlite decompaction. If Perlite decompaction is not required, the effective total savings would still be $103,400, leading to the conclusion that the savings warrants greater initial investment in the QSI.

2. 575,000 Gallon LH_2 Run Vessel

As shown in Table 6, the 575,000 gallon liquid hydrogen run tank will show a $422,540 potential total savings in five years by using QSI, taking into account operational savings and the greater original investment of $33,600 for a QSI-insulated tank. Of the total operational savings, $60,000 is attributed to three decompactions of the Perlite insulation during the five year period. If decompaction of the Perlite is not required, the effective total savings is still $362,540, leading to the conclusion that savings with QSI are so substantial in this case that any consideration of Perlite must be precluded.

C. CONSIDERATION OF INTANGIBLE OPERATIONAL COMPARISONS OF PERLITE vs. QSI

1. Maintenance and Repair

QSI compares favorably over Perlite when system maintenance is considered for the following reasons:

a. Maintaining a Vacuum

Mechanical vacuum pumps are required to maintain conditions in the annular space where Perlite is used as the insulation medium.

The annular space must be pumped down periodically because of the vacuum degradation resulting from the release of absorbed vapors from the Perlite. This will eventually break the degree of vacuum required to maintain high quality insulation.

"Getters" which cannot be used effectively in Perlite-filled annular spaces are used most effectively with QSI and the initial vacuum can be generally maintained without periodic re-pumping. The "getters" absorb any liberated vapors from the QSI and prevent build-up of gaseous hydrogen resulting from the hydrogen permeability through the inner shell of the vessel.

b. Repair

The Perlite system is at an extreme disadvantage as pertains to maintaining system components located in the annular space. In the event of a malfunction of the inner or outer vessel, interconnecting piping, or vacuum manifolds where Perlite is used, it would be necessary to break the annulus vacuum. Extreme care is called for in accomplishing this with a specified clean, dry gas or by clean, dry air (preferably heated). Thereafter, the Perlite wall must be completely removed or partially removed, at least down to the level at which the damage is suspected. During the time that repairs are being performed, any Perlite remaining in the annulus requires protection against the intrusion of moisture. All of the removed Perlite requires storage in a clean, dry area and needs to be completely covered to guard against moisture. Generally, moisture is the major problem when Perlite is used (see Figure 6). If the system malfunction has contaminated the installed Perlite by causing a significant amount of water or vapor to be deposited upon the material, the Perlite is not reuseable immediately. It must either be returned to the firing kilns for drying or be discarded entirely.

With QSI, the problem of entry into the annulus is almost non-existent. The clear 3-ft. annular space allows ready access to any portion of the vessel. It is necessary to remove insulation only at the site of the malfunction and then to the extent needed to effect repairs.

2. Blast Protection Factors

The aspects of protection for the inner shell of a dewar with the annular space filled with Perlite versus a QSI-insulated dewar are delineated in the following discussion.

a. Blast Effect

QSI offers no resistance to deformation of the outer shell with respect to the inner shell; therefore, it is not effective as a protective media. However, Perlite completely fills the annular space between inner and outer shell with a resilient 5-ft. layer of low-density material which will absorb the shock loads impinging upon the outer shell, thereby helping to prevent damaging distortions of the dual shell structure.

b. Shrapnel

Perlite will give added protection to the inner vessel against penetration by shrapnel because of its 5-ft. thickness of compacted insulating material. QSI provides practically no protection to the inner shell.

c. Weight Factor

Perlite-insulated vessels are more massive than equivalent volume QSI-insulated vessels. This added weight is a favorable factor in protecting the system against the effect of explosive over-pressure.

d. Shape Factor

Perlite-insulated vessels are approximately 4-ft. larger in diameter than the equivalent volume QSI-insulated vessels. This difference in diameter adds to the area which will be subjected to blast over-pressure and is a detriment to the system capability for resisting explosive over-pressure.

e. Shape Factor vs. Weight Factor

When considering the 575,000 gallon liquid hydrogen run vessel, Perlite-insulated versus QSI-insulated, the difference in weight is equal to 670,000 lb and the difference in projected area is equal to 380-sq. ft. Therefore, the over-pressure in lb/sq. ft. which would equal the weight advantage of the system is equal to 1770 lbs/sq. ft. or approximately 12 psi. If the expected over-pressure is multiplied by the load factor applicable to the circumstances and is greater than 12 psi, the vessel with the lower area exposure will exhibit the greater resistance to damage by explosive over-pressure.

IV. RECOMMENDATIONS

As a result of this study, QSI has been recommended over Perlite as the insulation for large dewar type liquid hydrogen storage and run vessels for the M-1 program. The relative advantage of QSI increases with the size of the vessel, number of chilldown cycles and expected life.

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