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Liquid Hydrogen in Nuclear Rocket Testing*

by

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INTRODUCTION

The large scale development of liquid hydrogen technology in the United States is largely due to the impetus it has received from the U. S. national aerospace program. One of the large uses in this program lies in the development and testing of nuclear powered rockets. In contrast to a chemical rocket in which combustion is required, a nuclear powered rocket needs only a working fluid to be heated and expelled as propellant. Hence in principle any fluid could be used. The ratio of thrust to rate of propellant expenditure (a measure of propulsion efficiency) has been called the specific impulse. It can be shown that this specific impulse is inversely proportional to the square root of the molecular weight of the exhausted propellant.⁽¹⁾ Thus hydrogen can be seen to be an attractive propellant. Consideration of the ratio of weight of container to weight of hydrogen can show that this ratio is hundreds of times smaller for hydrogen carried as liquid rather than as a gas.⁽²⁾ The importance of weight reduction thus dictates the use of liquid hydrogen as the propellant even though this introduces some additional operational problems, a few of which will be discussed later.

TEST PROGRAM AND FACILITIES

The development of the nuclear powered rocket is being directed by the Space Nuclear Propulsion Office which is a joint agency of

the United States Atomic Energy Commission and the United States National Aeronautical and Space Administration. The primary responsibility of the Rover Program, which is being carried out by the Los Alamos Scientific Laboratory, is to demonstrate the feasibility of the nuclear powered rocket and its first phase has been called KIWI. The operating principle of the KIWI reactor is represented schematically in Fig. 1. Here the cold hydrogen propellant enters the nozzle near its exit end, passes through the nozzle annular space for nozzle cooling, then through the reflector for cooling and finally through the core where it is heated before being expelled through the nozzle. The result of the KIWI phase has been the design, development, and successful testing of a reactor capable of operating on liquid hydrogen for extended periods of time at power levels of approximately 1000 megawatts (50,000 lb thrust). A subsequent program, the NERVA program, is charged with the responsibility of developing a flyable engine system using a reactor similar to that developed in the Rover Program.

All reactor full scale tests to date have been conducted at the Nuclear Rocket Development Station in Nevada. While several test areas are available for different test objectives, the most important test facility for liquid hydrogen testing is Test Cell "C", which is shown pictorially in Fig. 2. Liquid hydrogen storage consists of two 209,000 liter spherical dewars (190,000 liters or 50,000 gallons storage plus 19,000 liters ullage). These dewars are insulated with 90 cm of expanded perlite from which the atmosphere

is evacuated to a residual pressure of less than 10^{-3} torr. The dewar inner shell is fabricated of austenitic stainless steel and the vessels have a maximum allowable working pressure of 7 atmospheres. Daily loss of liquid hydrogen due to normal boiloff is approximately 0.2% per day. The gas phase inlet nozzle, which is used both for normal venting and depressurizing as well as gas pressurization during liquid outflow, terminates within the dewar in a horizontal hexagon made of 15 cm diameter pipe (see Fig. 4). Gas discharge holes are drilled only in the top half of the pressurization header to minimize any flow of input gas directly against the liquid surface. In this manner the liquid surface is not disturbed in the pressurization process and the liquid below the top few centimeters in depth remains subcooled. Figure 3 is a photograph of the dewars and Fig. 4 shows them schematically.

The liquid hydrogen transfer lines are 20 cm in inside diameter and are contained within a 25 cm diameter outer line which is evacuated to provide insulation (see Figs. 5 and 6). The outer line is equipped with expansion joints to prevent it hindering free contraction of the inner line upon cooldown. Sufficient flexibility is provided for the contraction of the inner lines by means of circuitous routing where required by the facility and by additional "U" bends where necessary. Where it is necessary to provide transfer line joints the regular vacuum jacket is interrupted leaving a short distance (approximately 40 cm) of bare inner line

into which is inserted a pair of flanges with a seal suitable for cold service. Auxiliary flanges on the outside of the vacuum jacket on both sides of the joint allow the placing of a concentric cover over the joint. When the joint and cover are assembled, subsequent evacuation of the volume inside the cover but outside the inner line provides a continuous vacuum insulation across the joint. Both inner and outer lines are fabricated of austenitic stainless steel. The pressure rating of the line upstream of the liquid hydrogen pump is 7 atmospheres while downstream of the pump the pressure rating is 82 atmospheres.

Liquid hydrogen is transported to the pump by pressurization of the storage dewars and sufficient pressurization is required not only for the system pressure drop but also to provide subcooled liquid at the pump inlet. It is for this reason that care is taken to introduce the dewar pressurization gas in such a way as to minimize liquid surface turbulence. The pump inlet liquid is generally less than 23°K with an absolute inlet pressure of 4 atmospheres. The difference between total pressure and vapor pressure of the inlet liquid is called the net positive suction pressure and in this case amounts to an approximately 2 atmospheres. An axial flow, seven-stage, high speed pump designed and manufactured by the Rocketdyne Division of the North American Aviation Corp. is used and is capable of flows on the order of 26,000 liter/min at pressures up to 70 atmospheres. Actually two such pumps are provided. A turbine-driven pump is used for reactor tests and the turbine energy source is ambient temperature hydrogen gas stored in the facility gas tank farm. An electrically driven pump (5,000 HP) is provided for a separate flow

system used for testing of components. Provision of demountable joints on both sides of a 90° elbow permits a connection to this flow system (the cryogenic engineering flow laboratory which is shown in Fig. 7). This laboratory, which therefore has available the same liquid hydrogen storage dewars described previously, is available for testing and evaluation of components during periods when reactor tests are not being carried out. The flow loop, which consists of the 20-cm inside diameter transfer line previously described, is in the shape of a U, 20 meters in total length. Two test positions are provided where the vacuum jacket widens to form either a vertical or horizontal test vessel suitable for inclusion of equipment within the jacket. In this manner equipment need not be specially vacuum jacketed for testing. One or the other (or both) of these vessels which are shown in Fig. 8 can be used for flow testing of transfer line seals, flow meters, valves, etc. The telemetering of controls and instrument readouts allows remote system operation and monitoring of supply dewar pressure, flow rate, and dewar temperature as a function of height. In addition, 94 instrumentation channels are available for telemetering of experimental measurements.

To date the reactor testing and cryogenic engineering flow laboratory testing at Test Cell "C" have consumed approximately 19×10^6 liters of liquid hydrogen.

The conclusion of the KIWI reactor testing is now being followed with the development of a higher powered reactor called Phoebus which will have a power capability of approximately 5,000 megawatts. Since

the testing of such a reactor requires larger flow rates as well as a longer test duration, an increase in storage as well as transfer rate capability of liquid hydrogen is required. In order to provide this, a modification of Test Cell "C" is currently under way. Two larger liquid hydrogen storage vessels are being constructed, each vessel having a liquid capacity of 1.9×10^6 liters (500,000 gallons) plus an additional 10% ullage. These vessels will also be insulated with evacuated perlite powder and the inner shell material will be austenitic stainless steel. The new transfer lines will have an inner line fabricated of Invar to minimize thermal stresses. Upstream of the liquid hydrogen pump the line will be 40 cm inside diameter and the pressure rating will be 7 atmospheres. Downstream of the pump the inside diameter will be 25 cm and the pressure rating is 135 atmospheres. The transfer line and pumping system will be capable of delivering propellant to the reactor at a pressure of 135 atmospheres at the rate of 130,000 liters per minute.

OPERATIONAL AND DESIGN PROBLEMS

In the design, checkout, and operation of the cryogenic systems at the Nuclear Rocket Development Station numerous problems have arisen. Most of them have been satisfactorily solved and a few are of continuing interest. Some of the latter are discussed below.

STRESS ANALYSIS IN LIQUID HYDROGEN TRANSFER LINES

As the size and complexity of liquid hydrogen transfer lines become greater the need for a careful stress analysis also increases. Stresses

due to transient temperature gradients during cooling of lines to operating temperatures must be evaluated as well as stresses at equilibrium conditions. As a rule at equilibrium conditions the only important stresses present are due to the inner line shortening caused by thermal contraction. The calculation of the resulting stresses is not complicated in principle. The determination of the stress at any point is based upon Castigliano's theorem which states that the derivative of the energy stored in the stressed piping system with respect to a force in a given direction is equal to the deflection in that direction.⁽³⁾ Energy storage is possible by several methods including bending, torsion, elongation, and shear. Input information required for solution includes piping geometry (at ambient temperature), coefficient of thermal expansion, Poisson's ratio of pipe material, final temperature, and a description of the type of supports, restraints, and anchors. For most problems of practical interest obtaining the solution is sufficiently tedious that the use of computer solution is desirable and several computer codes are written for this type of problem. Usually with such codes it is possible to divide the pipe into short longitudinal sections with varying temperature and in this manner the effects of axial temperature gradients can be included. Complications can arise in such calculations because computer codes are sometimes intended for long, slender piping systems and therefore ignore the elongation and shear modes of energy storage. Secondly, Poisson's ratio is frequently not well known over the temperature range of interest and finally the proper description of the

restraints, anchors, and supports may be very difficult and may not even be reproducible from one cooldown to the next. A typical transfer line section to be analyzed for cooldown stress is shown in Fig. 9. A flexibility analysis of such a pipe branch allows calculation of stresses and deflections. Where intolerable stresses or deflections are predicted these need to be alleviated by alternate pipe routings or other means.

For the calculations of stresses due to transient temperature gradients, it is necessary to postulate a cooldown model for cryogen flow and such a model is shown in Fig. 10. Here the transfer line is pictured at some time after cooldown has been started. The first part of the line which is already cooled nearly to liquid temperature is filled with liquid. Downstream of this there is a two-phase region where the pipe is being rapidly cooled by boiling liquid and further downstream warming gas is cooling the pipe more slowly. While this model is undoubtedly oversimplified for a microscopic description of the cooldown process, it describes the process well in a macroscopic way and its assumption permits calculation of pipe wall temperatures (as a function of length, time, and radius) as well as fluid temperature (as a function of length and time). The resulting radial temperature gradient in the pipe wall then permits calculation of stresses due to this gradient. It is of importance to note in the determination of stresses due to radial temperature gradients, that not only the ΔT across the pipe wall, but also the actual shape of the temperature distribution is important. Stresses due to radial temperature gradients within the pipe wall are usually tolerable, however,

in the case of high pressure flanges of large diameter, overstress can result from very rapid cooling of the transfer line. For such cases it is necessary either to precool the transfer line with a slow flow of cold gas (which could be obtained from the storage dewar boiloff gas) or perhaps with small pulse flows of liquid hydrogen. This slow precooling lowers the temperature uniformly until the system is cold enough so that flow of the cryogenic liquid cannot cause overstress on final cooling to cryogen temperature. These problems have already been encountered in another cryogenic installation in which high pressure flanges of 50 cm inside diameter are used.⁽⁴⁾ In this case precooling with cold boiloff gas from the liquid hydrogen storage is used.

In the operation of a cryogenic system, it is also possible to create circumferential temperature gradients which will cause bowing and bending of transfer lines. Additional stresses and large reaction forces at pipe anchors can be experienced and heavy equipment can be moved. (The test vessels shown in Fig. 8 were lifted off the floor during one test.) While the circumferential temperature gradient can arise in more than one way, perhaps its most common occurrence is in the cooldown of transfer lines. Usually some two-phase flow is encountered during the cooldown and if stratification occurs, the bottom of the pipe can cool faster than the top. One must therefore either carry out the cooldown with flow velocities sufficiently large to avoid stratified flow⁽⁵⁾ or provide sufficient flexibility in the system to allow the bowing to occur safely.⁽⁶⁾

TURBINE ENERGY SOURCE

To drive the liquid hydrogen pump for the previously mentioned modification of Test Cell "C," a large power source is required (greater than 50,000 HP). Because of remoteness from electric power sources (as well as slow speed of response to demands for flow rate changes) an electric drive was not considered desirable. Several alternate methods for driving a turbo pump were considered and these are shown schematically in Fig. 11. The method currently used (shown in Fig. 11a) consists of expanding (through a turbine) gaseous hydrogen stored at ambient temperature in steel vessels at pressures up to 240 atmospheres. Each such vessel contains up to 10^7 standard liters of hydrogen gas and the test cell modifications already described would require more than 50 such vessels. Since each vessel costs approximately \$100,000, more than \$5,000,000 would be required for gas storage alone. Furthermore the number of system valves (and consequently valve leakage problems) would be multiplied greatly. For these reasons a more economical solution was sought. Three other solutions which were considered are shown in Figs. 11b, 11c, and 11d, and the system shown in Fig. 11c was selected for testing. This system requires the use of hot water (93°C) as the energy source. The cold water effluent from the heat exchanger can be subsequently used to cool the reactor shield before being dumped. In this system the output stream from the liquid hydrogen pump is divided with the major portion going to the reactor while the smaller stream is passed through the inner tube of a countercurrent (water to hydrogen) heat exchanger.

The hydrogen leaving the heat exchanger, which is at approximately 300°K, is allowed to expand through the turbine to drive the pump. Startup can be accomplished with the use of a small quantity of gas from the existing tank farm. Since no data on large scale heat exchangers of this type was available, an intermediate scale, counter-current, liquid hydrogen to water heat exchanger was built and tested at Los Alamos. The inner tube (for hydrogen flow) was 2.25 cm in inside diameter and 12 meters long. Liquid hydrogen flows were up to 57 liters per minute. The outer (or water) tube was 3.8 cm in inside diameter and water flow rates through the annulus were up to 60 liters per minute. Above 120°K the heat transfer coefficients which were measured were approximately half of those computed of the Dittus-Boelter correlation.⁽⁷⁾ At lower temperatures, agreements were much worse with the measured values becoming even smaller. This was attributed to a cold "core" flow in the hydrogen stream.⁽⁸⁾ Introduction of a twisted tape turbulator raised all heat transfer coefficients approximately to computed values.

A full scale prototype (see Fig. 12) was next fabricated from aluminum and tested at the Nuclear Rocket Development Station with liquid hydrogen flows up to 4,900 liters per minute in a 12.5 cm inside diameter inner tube with longitudinal fins. The previously reported heat transfer coefficients were verified. Furthermore, the ice formation in the model and prototype tests was rapid, predictable, and presented no operational problems. While some flow and pressure

oscillations did occur it was possible to operate in such a way as to make their influence unimportant.

PERLITE COMPACTION

Large liquid hydrogen storage dewars (say greater than 150,000 liters) have usually been field fabricated, double-walled spheres insulated with an evacuated powder such as perlite. When the inner sphere is cold, a void is created beneath it by thermal contraction. If the powder falls into this space, then upon subsequent warmup it will be compressed or compacted by the expanding inner shell. This mechanism, if allowed to persist for several cycles, can then give rise to large forces on the inner spherical shell. The degree to which the powder does fall into the void is very difficult to predict and in the absence of vibration the void might never be filled. However, at least one case is known where support rods and interconnecting bellows have been ruptured by this process. Work at the Los Alamos Scientific Laboratory to date has attempted to determine the compressive forces where complete void filling occurs. Table I gives results of force vs. displacement measurements as applied to a 380,000 liter storage dewar insulated with a 90 cm thickness of evacuated powder. (9)

It should be remembered that these are maximum forces and it still remains to be determined under what conditions and to what extent they actually manifest themselves under field conditions. Should it turn out that such forces will always be present, a number of solutions to

the problem appear possible. These range all the way from changing to a different insulation system to merely designing the inner shell support system, manholes and interconnecting piping to allow the extra inner shell motion necessary.

DEWAR COOLDOWN

It is frequently of interest to compute the quantity of liquid hydrogen required to cool a large storage dewar to operating temperature. To start with a warm dewar and bring it to equilibrium operating conditions, it is necessary to cool the inner shell, cool the insulation and to provide for steady state boiloff caused by equilibrium heat input to the inner shell.

Computation of inner shell cooldown is usually done conservatively with the assumption that refrigeration equivalent to only latent heat of vaporization is obtained from the input hydrogen. If boiling is not so vigorous that liquid is entrained and carried out of the dewar by the boiloff gas, this assumption results in the maximum quantity of liquid useage possible. A minimum quantity of cooldown liquid could be computed with the assumption that the boiloff gas always leaves the dewar at the temperature of the inner shell at the instant the gas leaves. This condition, which can be fairly closely approached in the cooldown of long transfer lines, probably would not be expected to be approached in the case of cooling down storage dewars. Comparison of the above maximum and minimum quantities have been made for various cooldown conditions⁽¹⁰⁾ and it is seen that

there is possible a 5-fold variation in cooldown liquid requirement.

Liquid hydrogen requirements for insulation cooldown are considerably more difficult to estimate. Since the variation of effective thermal conductivity of evacuated perlite powder with temperature (and thickness) is not well known, prediction of the temperature gradient through the insulation is difficult. The temperature is usually assumed to be linear for ease of calculations, an assumption which is also very conservative. This allows the calculation of the total quantity of heat to be removed at any given radius (if specific heat is known as a function of temperature) and integration from inner to outer shell then gives the total heat removal necessary to establish temperature equilibrium. Since this heat is added slowly and presumably well after the dewar is filled, it would seem reasonable to assume it is absorbed only by boiling of liquid and hence only latent heat of vaporization is used in computing the consequent liquid requirements. The assumption of a linear temperature gradient is, since the shell radii are large, very close to the assumption of constant thermal conductivity. The latter assumption leads to an analytical expression for temperature in the insulation as a function of time and radius, and allows the calculation of heat input to the inner shell as a function of time. This result can then be presented as a graph of ratio of actual boiloff daily loss to steady state boiloff loss vs. time. This calculation has been made for the 190,000 liter dewar at Test Cell "C"⁽¹¹⁾

and predicts a period of greater than 20 weeks for boiloff to decline to 1.1 times boiloff at steady state.

In practice considerably shorter cooldown times are observed. Also smaller quantities of liquid are required for dewar cooldown than the above methods would predict. This can be seen from the experimental vs. computed results presented in Table II. Here it can be seen for the 3-week filling that the total quantity of liquid hydrogen used in cooldown was less than either of the predicted requirements for the shell or insulation cooldown. In the case of inner shell cooldown, the use of refrigeration from latent heat of vaporization alone is obviously too conservative. Something between the maximum and the minimum (mentioned previously as 1/5 of the maximum) would appear reasonable. In the case of the insulation cooldown, probably the greatest reason for the discrepancy lies in the assumption of the linear temperature gradient. (A secondary reason exists in obtaining additional refrigeration from warming of the boiloff vapors.) It is indeed highly conservative as has been pointed out⁽¹¹⁾ and the nonvalidity of this assumption might account for the faster temperature equilibration. To make a better calculation, one needs a better knowledge of thermal conductivity of perlite or better still a direct measurement of temperature gradients in representative thicknesses. This measurement will be made in one of the new dewars being installed in Test Cell "C". The actual cooldown requirements in Table II emphasize the variation in cooldown liquid requirement that can result from different cooling techniques.

The one-week fill consisted of filling the dewar as rapidly as was convenient considering the distance of the LH_2 production plant (Los Angeles) from Test Cell "C" (500 kilometers). In the 3-week fill, a 60,000 liter quantity of liquid was transferred to the dewar. After a period of one week a second 30,000 liter quantity was added. After another week the filling of the dewar was completed.

SAFETY

In the operation of large cryogenic systems, safety is always an important consideration. The safety of personnel is of course of paramount importance. However, it is also of importance to protect valuable equipment from operational damage. During any experiments at the Nuclear Rocket Development Station involving large quantity flows of liquid hydrogen, personnel are excluded from the experimental areas. During reactor runs, personnel are required to remain about 3 kilometers away from the test area for nuclear safety. In rooms through which there are large flows of hydrogen, oxygen concentration is reduced below the level necessary to support combustion by inerting with gaseous nitrogen.⁽¹²⁾ This is done because in case of a major line failure, ventilation adequate to avoid explosive mixtures would be impossible. Where hydrogen must be disposed of at low flow rates, such as normal dewar boiloff, these flows are vented directly to the atmosphere. High flow rates for venting during experiments flow into a common vent system and are burned in a flare stack. In places where liquid hydrogen leaking through a supposedly closed valve could be dangerous, a portion of the line is maintained

with helium gas at a pressure greater than dewar pressure. Analysis of the gas in this "helium block" section is made daily by gas chromatograph to avoid any air leakage into the dewar as well as unexpected hydrogen outleakage.

CONCLUSION

In the past years, Test Cell "C" has been checked out and operated without any major untoward incidents. In the past, minor modifications have been made but the first major modification, which involves increasing liquid hydrogen storage and transfer capability is now under way. This modification is the cause for the search for a more economical turbine energy source which in turn has required the investigation of heat transfer coefficients to flowing hydrogen.

The larger sizes of equipment result in an increasing need for careful thermal stress analysis of the cryogenic system as well as examination of cooldown liquid requirements and the possibility of mechanical forces arising from powder insulation.

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FIGURES

1. Kiwi reactor schematic
2. Test Cell "C" photograph
3. Test Cell "C" dewars (photo)
4. Schematic of Test Cell "C" dewar
5. Liquid Hydrogen Transfer Line under construction
6. Liquid Hydrogen Transfer Line
7. Cryogenic Engineering Flow Laboratory (schematic)
8. Cryogenic Engineering Flow Laboratory (photo)
9. Typical stress analysis problem
10. Cooldown model
11. Turbine energy sources
12. Heat Exchanger

TABLES

Table I - Perlite Compaction

Table II - Dewar Cooldown

Table I

Perlite Compaction
380,000-Liter Spherical LH₂ Dewar
Results of One Cycle, 300°K to 20°K to 300°K

Inner shell material	Stainless Steel	Aluminum
Perlite thickness	90 cm	90 cm
Inner shell contraction	1.37 cm	1.96 cm
Strain ($\Delta L/L$)	0.015	0.022
Pressure developed	.23 atm	.33 atm

Table II

Liquid Hydrogen Requirement
for Cooldown of 190,000-Liter Dewar

	<u>One Week Cooldown</u>	<u>Three Week Cooldown</u>	<u>Assumption</u>
Calculated shell cooldown requirement	2950 kg	2950 kg	Only latent heat of vaporization
Calculated insulation cooldown	<u>750</u>	<u>1760</u>	Constant thermal conductivity, latent heat only
Calculated total	3700	4710	
Actual requirement	2260	1090

Fig. 1

Fig. 2

Fig. 3

Fig. 10

TEST CELL 'C'- LIQUID HYDROGEN DEWAR

Fig. 4

No. 5

Fig. 5

Fig. 6

CRYOGENIC
ENGINEERING
LABORATORY

FLOW LOOP
TEST CELL "C"

Fig. 7

Fig. 8

8" VACUUM JACKETED
LH₂ PUMP DISCHARGE LINE

TANK FARM STORAGE

GAS GENERATOR

HOT WATER HEAT EXCHANGER

BURNER-HEAT EXCHANGER

Fig. 12