Problems in the Operation of Large Cryogenic Systems*

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ABSTRACT

The Los Alamos Scientific Laboratory has operated two liquid hydrogen test facilities for fourteen months at the Nuclear Rocket Development Station. These cells have the capability for transfer of liquid hydrogen at flow rates up to 100 lbs/sec and have a total storage capacity for liquid hydrogen of 156,000 gallons. A number of design and operational problems have been met, viz., stresses in 8-inch diameter transfer lines, times and quantities of liquid hydrogen required for cooldown of transfer lines, dewar instrumentation, gas requirements for pressurization of liquid hydrogen filled dewars, and techniques for warmup of large cryogenic dewars. Solutions to many of these problems are described and outstanding problems discussed on the basis of current observations. In addition, some techniques are described that are employed for safe operation of the liquid hydrogen facility, including helium block systems for leaky valves, room inerting to prevent fire or explosion in the event of a hydrogen leak, and the purity control of dewar pressurizing gases and the purity control of purges of gas and liquid hydrogen transfer lines. A brief summary is included of major modifications that are planned or underway for these test facilities.

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* Work done under the auspices of the United States Atomic Energy Commission

DISCLAIMER

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INTRODUCTION

For the development of nuclear reactors[1] suitable for use as a propulsion energy source, the United States Atomic Energy Commission has operating at the Nuclear Rocket Development Station in Nevada two large cryogenic systems for LH_2 storage and transfer. Details of these systems are being published elsewhere[2, 16, 17] and here it will be mentioned only in passing that the systems involved contain 8 inch I. D. vacuum jacketed transfer lines with an allowable working pressure of 1200 psig. In one case storage is provided for 56,000 gallons (Test Cell A) and in the other case 100,000 gallons of LH_2 (Test Cell C). The cryogenic systems of both test cells are now operative and in the past 14 months a total of seven hundred thousand gallons of liquid hydrogen has been used operationally. By and large this operation has been carried out as planned. However, some of the more important problems for which solutions were required (or still are required) are described in this paper.

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PROTECTION AGAINST HYDROGEN LEAKS

During non operational periods, it is necessary to obviate unexpected entrance of hydrogen into areas where its presence is not desired. Due to leakage across the blocking valve seats, single or even multiple valves closed in series do not afford positive protection against this leakage. Such protection has been afforded by a "helium block" system consisting of two closed valves in series which contain helium gas at a pressure in excess of the storage dewar standby pressure. Operating procedure for maintaining and operating this system are discussed below.

During operational periods, large quantities of liquid and gaseous hydrogen are passed through sensitive equipment - the liquid hydrogen pump system, flow measuring systems, and control valves - and it is doubtful that sufficient ventilation could be provided to avoid the presence of explosive mixtures in case of massive failure of the lines or components. Consequently all enclosed spaces through which liquid hydrogen must pass in large quantities are inerted before test commencement. Nitrogen gas from the tank farm is discharged at various points around the room perimeter at floor level. Nitrogen is flowed into the room until the oxygen concentration is below 3%. Gas flow is then stopped until, because of air leakage and diffusion, the 0_2 concentration increases to 5% at which time gaseous N_2 flow is reinitiated. Representative results for

for the two test cells are given in Table 1.[3] The difference between the two test cells is attributed to the better room seal accomplished at Test Cell C. At Test Cell A a flow rate of 2.6 lb/sec gaseous nitrogen is used while the flow rate at Test Cell C is 7.8 lb/sec. Use of this inerting procedure has allowed over one year's operation with no fire damage even though massive hydrogen leaks have occurred.

GAS PURITY ANALYSIS

A gas chromatograph, described in more detail separately,[4] has been used since the startup of the liquid hydrogen facility to monitor gas purity. The limits on observable impurities are ~ 100 ppm H_2, 5 ppm O_2, and 5 ppm N_2. Hydrogen gas used for dewar pressurization is stored with an impurity of less than 25 ppm by volume. It is delivered to the dewars during operations through lines that have been previously purged. The purge is monitored for completeness and with the aid of analyzed samples more efficient use is made of the purge gas. The hydrogen concentration is monitored daily in the helium block systems and these systems are repurged if the impurity concentration exceeds 500 ppm.

During the start up of the room inerting system, a series of samples were taken at various locations in the rooms during inerting to observe the completeness and uniformity of the nitrogen concentration. Variations in oxygen concentration around the rooms and at different heights were found to be not greater than 1%. On this basis the procedure for reinerting was devised.

The analysis of impurities collected in a large dewar and then boiled off during a periodic warmup was performed. For a 50,000 gallon dewar in use for six months the total impurity was found to be ~ 1/10 gram a quantity not considered dangerous, but reason enough to continue periodic dewar warm up.

STRESS ANALYSIS

The primary cryogenic piping systems consist of pump suction lines which are 8-inch I. D. stainless vacuum jacketed pipe rated for 100 psig (wall thickness of .109 inch) and pump discharge lines of 8-inch I. D. stainless vacuum jacketed piping designed for 1200 psig (wall thickness of .322 inch) service. Because of the inaccessibility for repair and because of the high pressures involved, no bellows or other motion compensation devices were incorporated in the inner line. Instead, motion of the inner line is permitted by expansion loops. The vacuum jacket contains enough bellows to allow adequate freedom and is constrained to follow the movements of the inner line. In order to verify the suitability of the design for the intended service, it was necessary to examine in some detail the stress developed in the inner line.

Stresses arising from several types of loading were considered, specifically: thermal contractions, internal pressure, wind loading, dead weight, flow perturbations, vibration of associated equipment, and bowing due to circumferential temperature gradients. The problems of bowing have been eliminated through the use of careful cooldown procedures.[5] Stresses due to internal pressure are easily calculated by standard methods, and are usually small. Also, in the ASME code specifications, internal pressure is included in determining the allowable stress range for stresses due to thermal contraction.

The dead weight of heavy components such as valves is largely taken care of by vertical supports and spring hangers. The most probable source of vibration, the turbopump, is isolated from the system by bellows and anchors. Dynamic loadings - wind and flow perturbations - will be discussed below. The most significant source of stresses is thermal contraction, and the greatest effort was applied toward understanding the stresses arising in this way.

A calculation of the deflections and stresses to be expected upon cooling the pipe from 540°R to 38°R was done by The Service Bureau Corporation for the piping contractor prior to construction of the cryogenic transfer lines. The values obtained were compared with allowable stress ranges specified by the ASME piping codes. In obtaining these ranges, no account was taken of the greater strength of stainless steel at cryogenic temperatures. Examination of the calculated values showed some elbows to be overstressed. These were replaced with heavier elbows, bringing the entire system within code limits.

As a check on the first calculation, an independent analysis of several sections of line was made using the G. E. piping stress program L03812. The program is based upon Castigliano's Theorem: The deflection in the direction of and at the point of application of a force, F_p, is given by the partial derivitive of the strain energy in the piping system with respect to the force, F_p.[6] In addition,

measurements have been made of the displacements during cooldown of the lines at Test Cell C. In general for the short runs of pipe anchored at either end, the observations agree with calculations more closely than for longer sections of line. The 93 ft. long section between the dewars and pump at Test Cell A was analyzed by the contractor and by L03812. The agreement between the analyses in predicted displacements was very close, usually within a few percent, and differing by, at most, 10%. However, the stresses predicted by L03812 were up to 30% less than those of the contractor's analysis, and were distributed somewhat differently.

The piping at Test Cell C was analyzed by the contractor and by L03812. On the piping, the two methods predicted stresses that agree well, but differ on predicted displacements. Particularly, L03812 predicted displacements in one direction which seem unusually large. Linear potentiometers were installed at eight points where large displacements were predicted. The amplified data was recorded on Sanborn recorders and calibration was performed prior to each cooldown. The measured displacements agreed in sign with the two calculations but disagreed in magnitude, tending to fall between the predicted values. The measured displacements are not completely reproducible from cooldown to cooldown. This appears to be due to friction in the supports. There are several types of supports, such as stands with pads which slide on concrete, and valve hangars which are difficult to describe within the limitations of present piping flexibility analysis. A model of the Test Cell C pump discharge line is under construction, and data from this model should define the reliability of each of the stress programs.

The problems of stresses due to dynamic loadings is also undergoing further study. Flow oscillations are normal during line cooldowns, and some oscillation can be expected during reactor operation. Water hammer effects due to operation of control valves for fast flow shut down or during frequency response measurements have been observed. It is not anticipated that the associated stresses will be very great, as all observed displacements have been small (no greater than 0.5 inches peak to peak), but the problem is under study.

Dewar Pressurization

The quantity of gas required to pressurize a large dewar containing liquid hydrogen has been measured for the 50,000 gallon vacuum perlite insulated spherical dewars at the Nuclear Rocket Development Station. The dewars may be pressurized through a 6-inch diameter pipe that has been formed into a hexagonally shaped gas diffuser ring located in the ullage space. Gas from high pressure storage bottles can be admitted through a sonic orifice which has been instrumented with differential and upstream pressure transducers and an upstream temperature transducer to allow calculation of a mass flow rate.

The dewar instrumentation of use for these measurements consists of a series of platinum resistance thermometers located along the dewar vertical axis. From these a temperature profile of the ullage gas and of the liquid may be obtained. If the inner dewar shell is assumed to be non-heat conducting (as a stainless steel shell it approximates this condition) then the isothermal surfaces in the gas space will be represented by a series of plane disks perpendicular to the dewar axis. The observed profile can be used to compute the quantity of hydrogen gas in the ullage space before and after pressurization.

Comparison of these three numbers, the mass flow rate integrated over the pressurization time and the ullage gas quantity

before and after pressurization, will yield a value of the condensation or vaporization that occurred during the dewar pressurization.

As an example the nearly full dewars were pressurized from 17 psia to 73 psia in 30 seconds. During this time the heat leak into the inner shell was 20 BTU based on measured loss rates under quiescent conditions, which is quite negligible, and lends support to the above model of a nonconducting wall. The dewars were filled to 98.6% and 91.8% of the rated capacity which gave a total ullage volume of $1.98 \times 10^3 ft^3$, exclusive of the volume in the pressurizing lines. From the mass flow rate measurements 24 lbs. of hydrogen gas entered the dewar during pressurization. Using the observed temperature profile changes and the plane disk model the increase of the mass of gas in the ullage space was calculated to be 142 lbs. Therefore it may be concluded that a net vaporization occurred.

A number of models have been proposed to study the condensation of gases used to pressurize containers of cryogenic fluids [7-11]. Although the "worst case" model of R. W. Moore et al.,[9] does suggest a net vaporization for the case of hydrogen pressurization of liquid hydrogen this model assumes complete equilibrium between the hydrogen gas and liquid during the pressurization. As the Figures 1A and 1B indicate, the temperature profile of the dewar during pressurization demonstrates that no gross turbulence has occurred, and suggests that the gas diffuser ring has introduced the pressurization gas on top of the existing ullage space gas.

It is possible that local turbulence has occurred to produce the net vaporization. Furthermore considerations from an energy balance indicate the decrease in enthalpy of the entering gas is just sufficient to provide the latent heat of vaporization for the net increased mass of gas after pressurization minus the gas added from the outside.

The construction of a 100,000 gallon dewar at Test Cell A provides an opportunity to extend the instrumentation for study of the dewar pressurization phenomena. In addition to the series of platinum resistance temperature transducers located along the vertical axis of the dewar, a second vertical array of temperature transducers is planned off axis to allow estimation of the degree of turbulence and the correctness of the plain disc model used in calculations of the total ullage gas mass.

Cooldown Calculations and Measurements

Continuing the work of Bronson et al. [5] the method for cooldown suggested by Burke [12] has been written into an IBM 704 program. The full method was used including an average thermal conductivity for the transfer line under consideration. This extends the treatment from vacuum jacketed to nonvacuum jacketed lines. In addition the program was so devised as to calculate from the initial pressure, lengths of line, and vent valve size whether the flow would be sonic or sub-sonic, and the mass flow rate was calculated from the appropriate relations [14]. Calculations using the NBS method [13] have been extended to include the heat transport into the transfer line as a function of time and have been compared with the method suggested by Burke.

The test facilities in Nevada have provided experimental data for comparison of these cooldown calculations. At each test cell there is provision for a return liquid loop which may be substituted for the spool piece that connects the reactor cart with the facility piping. This provides a series of different combinations of lines and vent valves used in cooldown with liquid hydrogen and liquid nitrogen. Cooldown of the 8-inch diameter cryogenic lines is accomplished using an Annin plug-type valve as the vent control valve. The vent valve used an equal percentage-type plug and was air actuated remotely. Table 2 collects the calculations and observations.

During the first liquid nitrogen cooldown at Test Cell A, the pump discharge to vent valve was inadvertently left open, and the entire quantity of liquid nitrogen stored in one dewar was used before line cooldown to this intermediate point was stopped. The calculations attempt to represent this situation. For the first liquid hydrogen cooldown at Test Cell A the vent valve was not fully open so that the cooldown time predictions on the basis of a full open vent must be lengthened by some unknown quantity. Liquid hydrogen cooldown during run EP III at Test Cell A was a cooldown under subsonic conditions at the vent valve. The calculations in both cases predict times shorter than those observed although difficulties with the data collection system allow only a lower limit to be set on the cooldown time. The first liquid nitrogen cooldown at Test Cell C used the return line and a procedure using two vent valves was introduced to assure that the flow would be nonstratified two-phase flow during the initial part of the cooldown [5]. Although the instrumentation was inoperative during this cooldown, visual observation of the venting gas indicated a time greater than 1000 seconds was required for cooldown. The first liquid hydrogen cooldown at Test Cell C used two vents one of which was partially open and agreement with the NBS calculation is satisfactory. A rather wide discrepancy between the NBS calculations and the Burke method is noted. However the Burke method is not adaptable to adjustments of vent valves during the cooldown. For cooldown from the

dewar to the vent valve upstream of the reactor at Test Cell C, data taken at two different dewar pressures are compared with calculations.

Comparison of the observations with calculations based on the Burke method and on the NBSmethod of cooldown time prediction suggests that real variations exist between the data and calculations. These deviations may be in part accounted for by having a sonic orifice at the vent valve which is far from ideal. In part the calculations are influenced by the fixed assumptions required in each method and inapplicable over a wide range of experimental conditions. For the liquid hydrogen data using the Burke method, a thermal conductivity of 4.3×10^{-5} BTU-inches per square foot degree Kelvin, a specific heat of the pipe of 0.1547 BTU per pound degree Kelvin, and a vent gas average temperature of 140°K are used. A line is called "cooled down" when most of the fluid appearing at the vent line is liquid. This is easily observed experimentally with a narrow range temperature transducer that over a period of 2 or 3 seconds oscillates between liquid and gas temperatures.

DEWAR WARMUP

Beginning on January 15, 1963, the dewars at Test Cell A were warmed as part of a routine inspection program. Each dewar is a 28,000 gallon horizontal cylinder. The inner shell is stainless steel 3/8-inch thick, and is insulated with 14-5/8 inches of evacuated perlite. The liquid in the dewars was drained, and the warmup was then begun by breaking the insulating vacuum of each dewar with approximately 800 SCF of nitrogen gas. Instrumentation available for monitoring the dewar temperature vs. time consisted of 12 platinum resistance thermometers located within the storage volume of the inner shell. The range of temperatures indicated by these thermometers is shown in Figure 2. The theoretical curve of wall temperature vs. time also shown in Figure 2 was based upon a method presented by the National Bureau of Standards [15]. As can be seen, the actual temperature follows rather well the predicted values, except for the area around 72 hours, which is believed to be caused by a data system malfunction. Although the instrumentation did not measure wall temperature directly, the warming was slow and it is felt that the higher temperatures measured at any time probably represent the wall temperature closely.

Data recording was not made beyond 136 hours. However, before the dewar could be conveniently entered, it was necessary to raise the inside temperature above the local daytime dew point.

The greater part of a week was required to accomplish the last several degrees of the warmup due to the facts that the temperature gradient was small and the nighttime temperatures were low. Because of this experience, it is strongly recommended that heating devices be incorporated in the construction of large dewars, and the 100,000 gallon dewar to be constructed at Test Cell A will incorporate a dewar heater.

FUTURE PLANS

In order to permit both longer duration runs as well as higher flow rates, both Test Cells A and C are now undergoing modifications to the cryogenic storage and transfer systems. A 100,000 gallon spherical storage dewar is under construction at Test Cell A. This vessel will be insulated with evacuated perlite. Criteria are presently being developed for the Test Cell C modification. Tentatively Test Cell C will have added a 500,000 gallon liquid hydrogen storage and run dewar having evacuated perlite insulation. Transfer lines with a 12-inch I.D. are planned.

As discussed above, a second set of platinum temperature transducers will be installed off axis in addition to the set planned for the vertical dewar axis. A continuous reading capacitance gauge will be installed and a series of thermocouples will be attached to the outer surface of the inner shell. Provision will be made for a differential pressure gauge although instrumentation will not be installed. Neither the load cell weigh system nor the vapor pressure bulbs currently installed on all test site dewars are planned for installation on the new dewars.

In addition to these two modifications, criteria are being established by the Los Alamos Scientific Laboratory for a new test cell, designated Test Cell E. Test Cell E is expected to have 1.2×10^6 gallons of liquid hydrogen storage and to be capable of

transferring liquid hydrogen at rates up to 120,000 gallons per minute at pressures up to 2000 psi.

For the Test Cell C modification as well as Test Cell E, criteria for the type of line joint and insulation are yet to be specified. The present piping joints are made with 600 lb. ASA flanges. However the increased size and pressure ratings being considered will require that every effort be made to reduce as much as possible the mass of couplings to minimize both quantity of liquid hydrogen as well as time required for cooldown.

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Table I

Shown in the table are room volumes and numbers of room volumes of nitrogen gas used to inert the rooms and maintain them with an oxygen concentration less than 5%.

Test Cell	Room Volume (ft^3)	Room Volumes to inert to 3% O_2	Time to inert to 3% O_2 (min.)	Room Volumes per hour to maintain less than 5% O_2
A one room	18,000	2.9	25	1.9
C five rooms	75,150	2.5	30	1.3

Table 2

Times τ and quantities M required to cooldown transfer lines with liquid hydrogen. Calculations based on the Burke method and the NBS method as described in the text are compared with observations.

Test Cell	Line	Burke		NBS		Observed	
		τ(sec)	M(lb)	τ(sec)	M(lb)	τ(sec)	M(lb)
A Dewar to LN_2	Pump P = 45 psig	-	-	645	(12,500)	< 887	(12,500)
A Dewar to LH_2	return P = 45 psig	< 180	< 243	-	-	315	-
A Dewar to LH_2 EP III	return P = 50 psig	163	217	200	237	> 270	-
C Dewar to LN_2	return P = 50 psig	1170	3634	1260	4400	(see text)	
C Dewar to LH_2	return P = 50 psig	342	413	540	614	560	-
C Dewar to LH_2	reactor P = 80 psig	190	243	-	-	251	329
C Dewar to LH_2	reactor P = 60 psig	413	154	200	260	405	181

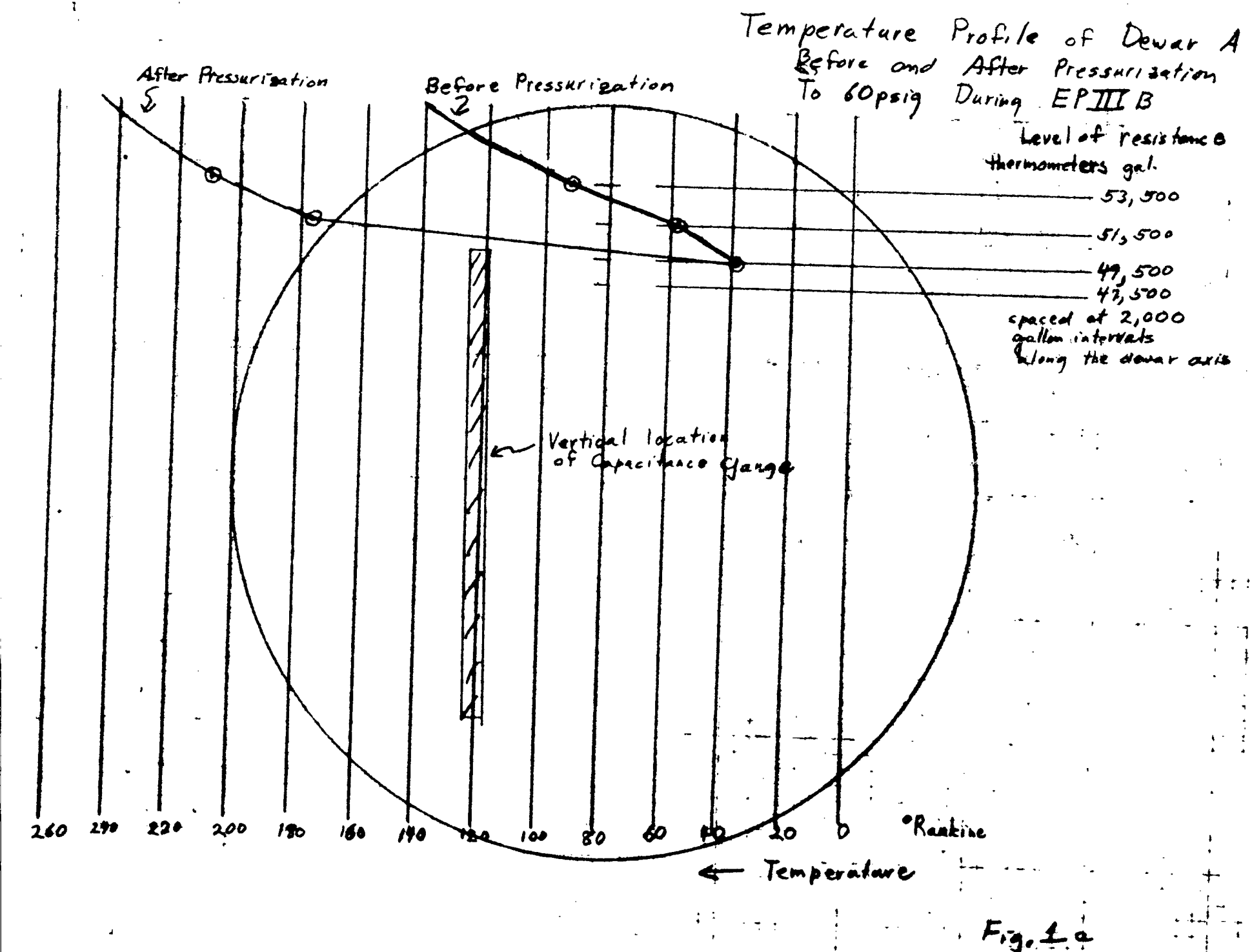
Temperature Profile of Dewar A
Before and After Pressurization
To 60psig During EP III B
After Pressurization
1
Before Pressurization
2
Level of resistance thermometers gal.
53,500
51,500
49,500
47,500
spaced at 2,000 gallon intervals along the dewar axis
Vertical location of Capacitance Gauge
260
240
220
200
180
160
140
120
100
80
60
40
20
0
°Rankine
Temperature

Fig. 1 a

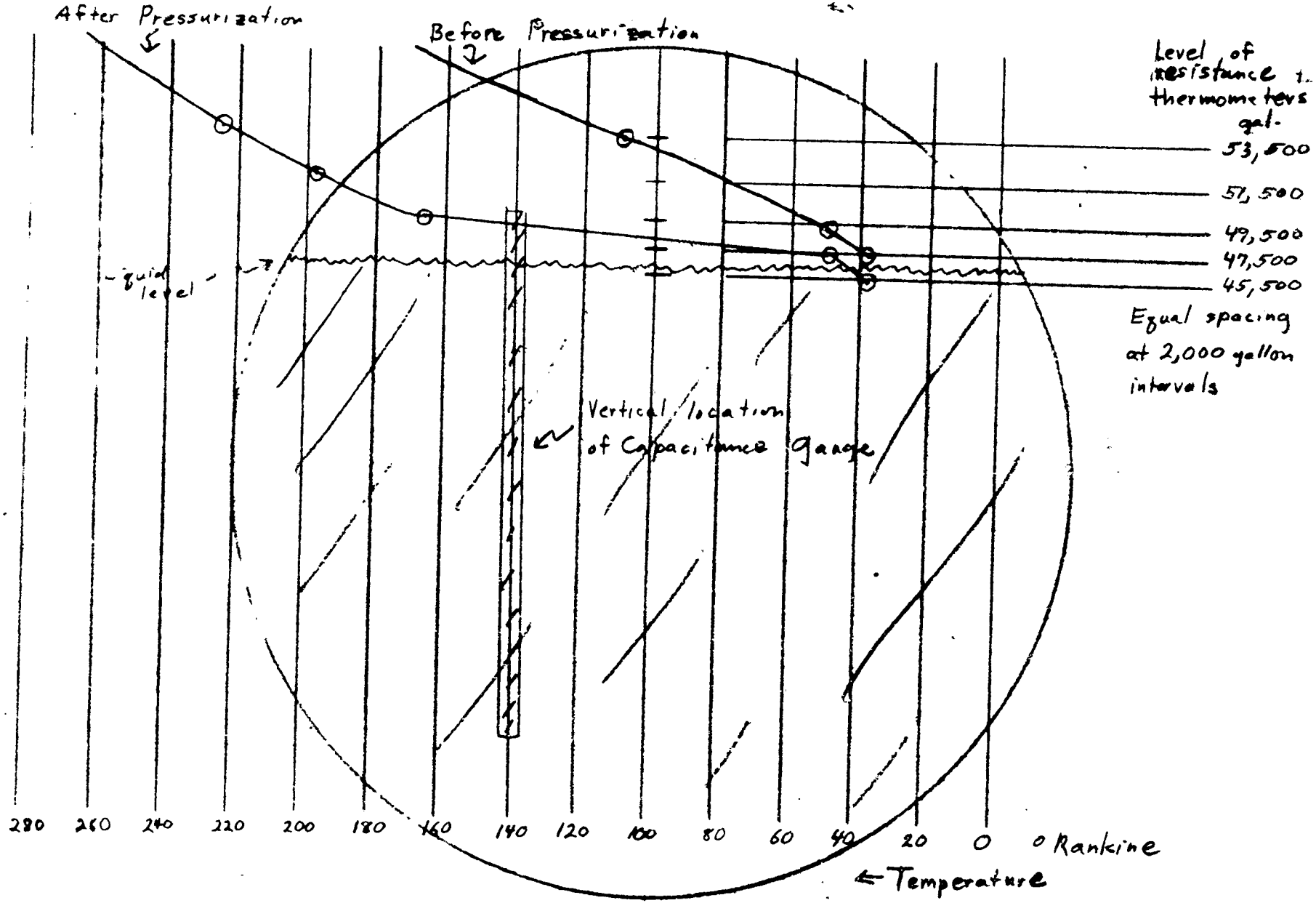

Fig. 1b Temperature Profile of Dewar B Before and After Pressurization to 60 psig During EP III B

Fig. 2

HIGH TEMP. IN DEWAR

LOW TEMP. IN DEWAR

THEORETICAL DEWAR TEMP.

TEST CELL A DEWARS — WARMUP

Beg 4:44 1-15-63

TIME — HOURS