D26

JOULE-THOMSON VALVES FOR LONG TERM SERVICE IN SPACE CRYOCOOLERS

James M. Lester and Becky Benedict

Cryogenics, Space Systems
Ball Aerospace Systems Division
Boulder, CO 80306

Joule-Thomson valves for small cryocoolers have throttling passages on the order of 0.1 millimeter in diameter. Consequently, they can become plugged easily and stop the operation of the cooler. Plugging can be caused by solid particles, liquids or gases. Plugging is usually caused by the freezing of contaminant gases from the process stream. In small open loop coolers and in closed loop coolers where periodic maintenance is allowed, the problem is overcome by using careful assembly techniques, pure process gases, warm filters and cold adsorbers. A more thorough approach is required for closed loop cryocoolers which must operate unattended for long periods. This paper presents the results of an effort to solve this problem. The causes of plugging are examined, and various ways to eliminate plugging are discussed. Finally, the development of a "J-T defroster" is explained. We conclude that a combination of preventive measures and a defroster will reduce the chance of cooler failure by plugging to such a degree that J-T coolers can be used for long term space missions.

Key words: J-T cryocooler, J-T defroster, J-T valve, long life mechanical refrigerator, space cryocooler

1. Introduction

Typical space cooling applications now being considered are for instruments costing upwards of one hundred million dollars. The required operating lifetime of these instruments is 5 to 10 years without maintenance. One watt of cooling at less than 10K is a typical goal. There is a desire to start these missions in less than 5 years; but, to develop a reasonable chance that such missions can be accomplished, a great deal of successful cooler testing must be done. Ideally, we would like to have many of the coolers operating for longer than ten years before risking huge sums of money on entire instrument systems. Temperatures less than 10K for sufficiently high cooling power have not even been demonstrated for space cooler configurations, much less in any statistically significant way. Realistically, we will not have the luxury of completing statistically significant life testing before a large risk is taken.

In view of this situation, a good design approach is to use the hardware concepts which best avoid the need for extensive life testing and will still do the job. In cryocoolers, machines which do the best job of avoiding the uncertainties of wear, fatigue, critical materials and contamination are favorable at this time. The passive Joule-Thomson (J-T) cold section does this very well except for the plugging problem due to contamination. Test time limitations make it difficult to guarantee that a J-T cooler will not freeze up in 10 years even if traditional purification techniques are applied to the fullest extent possible. This leaves us with an unacceptable risk which must be overcome by some other means.

Fortunately, we can employ a strong countermeasure - namely a defroster, to clean out the J-T valve. Many short duration tests can then be run under severe contaminating conditions in an attempt to show that this cleaning process will always renew the cooler. Then, in flight, under less severe contaminating conditions, the cooler can be "defrosted" on a preset schedule more frequently than the statistically proven safe operating interval. Confidence in the cooler will then be developed on a cycle basis rather than on a total time basis, thus allowing greatly accelerated testing.

We concluded that the plugging problem should be solved prior to refining other components in the J-T system because it is the key to determining if J-T's are usable for long term missions. We are currently developing a J-T valve and defroster with encouraging initial results. This paper describes that work.

2. The plugging problem in J-T coolers

This paper is primarily concerned with small cryocoolers for use in space instruments. Table 1 gives approximate design values which relate to the plugging problem for a 1 watt Helium J-T stage operating between 16 and 1.6 atmospheres.

Table 1 - Approximate cooler characteristics (Example)

• Helium Flow rate	1 Standard ℓ/sec
• Helium Quantity Required to charge the stage	10^2 Standard ℓ
• Cryocooler area which outgasses into the Helium	10^3 cm^2
• Volume of a plug in the J-T valve (Assumes 0.1 mmDia-by0.1mm long plug)	10^{-6} cm^3
• Volume of a plug in the small heat exchanger tubing upstream of the J-T valve (Assumes 2mmDia-by20mm long plug)	$10^{-1}cm^3$
• Operating time - 10 years-approx.	10^5 hours

The geometry of the J-T valve is assumed to be a short small hole, and this sets the size of its plug. The upstream high pressure side of the heat exchanger is characterized by a single line of small diameter tubing. Plugging by freezing of the mixture of contaminants will be spread over a considerable distance in this tube as dictated by the flow, temperature gradients and freezing points of the various contaminants in the mixture. We suspect that the assumption of a ten diameter freezing zone is a low estimate; but, the point to be considered is that the volume of contaminant required to form a plug is several orders of magnitude greater in the heat exchanger than in the valve itself. The downstream, low pressure side of the heat exchanger is much larger as dictated by the requirement for low pressure drop in the compressor return, so there is much less concern about plugging there.

2.1 Sources of contamination

Potential contaminants are gases, liquids or solid particles. Particles are dirt or chips left in the cooler during construction and dust from adsorbers. Liquids are things like free water or oils, the latter possibly from an oil lubricated compressor. There are three sources of gas: outgassing from the interior surfaces of the entire cooling loop, trace contaminants in the initial charge of Helium, and continuous vaporization of a cooler component. Plastic parts or oil in a compressor fall into this last category. The potential for plugging the example cooler of table 1 was estimated by calculating the sizes of these sources.

2.2 Gaseous contamination

The classical view of metal surface outgassing is given in [1]. This data shows that the outgassing of initially "clean and dry" surfaces at room temperature decreases from a fairly consistent value of

$10^{-8} \frac{\text{STD cm}^3}{\text{cm}^2\ \text{Sec}}$ after one hour in vacuum to $10^{-9} \frac{\text{STD cm}^3}{\text{cm}^2\ \text{Sec}}$ after ten hours and continues to decrease

by another order of magnitude for each additional order of magnitude span of time. The outgassing of a cooler, at least in the warm areas, will be roughly the same into a charge of pure Helium where the partial pressures of the contaminants are very low.

The outgassing relates to the potential for plugging in a logarithmic manner. In the first logarithmic time interval of outgassing, 1-10 hours, the outgassing will accumulate the equivalent of 160 plugs in the J-T valve and $1.6(0^{-3})$ plugs in the heat exchange tube upstream the J-T valve. The density of the frozen plug is approximately 10^3 times greater than standard density of the gaseous contaminant. Continuing from the second time interval, 10-100 hours, to the last, 10000-100000 hours, the total accumulation is about $8(10^{-4})\ cm^3$ of solid, or about 1 milligram. This amount could produce 800 plugs in the J-T valve. (Note that the amount of outgassing by this theory is the same for each time interval. Note also that the heat exchanger is relatively immune to plugging by gaseous contaminants because of its relatively large size.)

If ultra pure grade Helium is used for the initial charge, the total quantity of contaminants is about the same as the 10 year outgassing. Typical specifications for maximum contaminants in ultra pure Helium and the resultant amounts in the initial charge of 10^2 standard liters include trace amounts of C_2, N_2, Ne, Ar, H_2, CO_2, and H_2O (greatest contaminant listed first). The total amount of solid impurities is about $(10^{-3})\ cm^3$ or about 1 milligram. This amount could produce 1000 valve plugs.

Lastly, the system may have components which vaporize continuously throughout the operating period. Plastic parts or compressor oils are in this category. A good oil will have a vapor pressure of 10^{-10} torr at 300K. The amount of oil vapor (apart from free oil droplets) circulated toward the J-T valve would be that amount which saturates the process gas at the oil vapor pressure. If one standard liter per second of Helium flows in the system and the pressure is 1.6 atm at the oil vapor pickup point, the total amount of oil vapor frozen into solid form would be $3(10^{-5})\ CM^3$. This is enough to produce about 30 plugs.

A loaded adsorber can act as a continuous source of contamination if left "wet" from a previous test, and be a large additional source. In summary, over 2000 potential J-T valve plugs can be present in the system due to gaseous contaminants.

2.3 Liquid and solid contamination

Plugging due to free water is possible if the system has been left open to the atmosphere. Oil mist (suspended droplets) from compressors may be present in large quantities. Dirt and chips can be left in the cooler during manufacture. Residue from soldering operating has been known to dislodge and stop at J-T valves. Most J-T coolers use adsorbers which consist of charcoal particles or molseive pellets. These adsorbents lose fine dust particles and these are a concern because they are not easily filtered without creating the risk of freezing contaminant gases at the filters.

2.4 The nature of plugging

In spite of the large potential for becoming plugged, J-T coolers usually work. Plugging most often occurs during startup or after a power interruption, when the heat exchangers are warm and will not "cold trap" the contaminant gases. If the initial cool down period is passed, the cooler will usually continue to work. The reason is that the heat exchangers do a very good job of collecting the contaminants before they get to the J-T valve. Then also, the contaminants which do not stick to the heat exchanger walls are mostly in the form of minute ice crystals which are simply blown through the J-T valves. Sometimes coolers will operate at different cooling capacities on separate cooldowns - an indication of partial plugging.

3. Solutions to the plugging problem

Plugging of the J-T valve can be reduced or eliminated by three major techniques: reduction of contamination sources, the use of certain valve geometries, or by methods which counteract the contamination within the system when it is operating. While large improvements can be made with the first two techniques, the potential for plugging still exists. Counteractive measures are necessary. In the final analysis, renewing the valve by defrosting is the surest way to ensure long-term operation.

3.1 Reduction of contamination sources

Initial thorough cleaning and vacuum baking is necessary to reduce massive quantities of contaminants. It is not likely that the outgassing rate can be reduced to below

$10^{-12}\frac{\text{STD cm}^3}{\text{cm}^2\ \text{Sec}}$ therefore a significant potential for plugging will still exist in the system.

Research grade gases can be used to charge the cooler instead of ultra pure grade, reducing the potential for plugging by a factor of 5. Careful control of the charging process is necessary to maintain this improvement. All cooler components should be low vapor pressure materials. Careful design will ensure that the gas produced by these sources is a small fraction of the total contamination. As a general guide, materials with vapor pressure above 10^{-10} Torr should be avoided.

Compressors should either be oil free or should have a very low output of free oil droplets in mist form. The space in and around the J-T valve itself can be treated as a critical component and assembled in the strictest clean room conditions. This will virtually eliminate the chance of plugging by particles in the cooler if the valve capsule is protected by suitable filters.

3.2 Valve geometries

Most J-T valves are simple, short circular holes. Other geometries are possible, but there is little to be gained by these designs and they may be harder to unplug. A long capillary tube could be used as a J-T expansion device, allowing the flow passage to be larger in diameter. The flaw in this idea is that total plugging of the valve is not the only concern. Partial plugging in a long capillary could cause a large change in performance and is not allowable. The idea of using a porous plug suffers from the same flaw. In addition, the very fine pores of the plug will be much more easily plugged by minute ice crystals suspended in the stream.

One attractive compromise geometry is to put a wire through a small hole. This arrangement distributes the orifice into a ring shape which is not sensitive to plugging by a few particles left in the cooler during assembly.

3.3 Counteractive measures

Starting from the warm high pressure end of the system, there are a number of things that can be done to reduce the chance of plugging. In a cooler using oil lubricated compressors, virtually all of the free droplets must be removed by coalescing filters. Fortunately, these filters can be made very long and efficient since they are in the warm areas. Barrier film techniques are also necessary to prevent creep of oil films down the heat exchanger tubing. The more critical problem here is to reduce the mass of free oil to a level lower than that required to saturate downstream gas adsorbers and cause freeze up by that mechanism.

Adsorbers consisting of beds of charcoal, silica-gel, or molecular sieve materials are the most effective way to reduce the flow of contaminants to the J-T valve. Adsorbers in the cold areas just upstream of the J-T valve are very powerful purifiers, possibly eliminating the plugging problem completely, but the problem is in the proof. Several imperfections inherent with adsorbers may allow plugging to occur after a long period of operation. If the beds are made too 'tight' then they themselves may become subject to plugging. Channeling may occur leading to variations in purification efficiency from bed to bed. Adsorbers in flow streams tend to act as chromatograph columns. That is, concentration fronts gradually migrate to the downstream side and eventually a large release of adsorbed contaminants will occur. This effect has been observed in helium liquifiers causing unexpected freeze up after a long period of normal operation.

Particle filters such as screens or porous metals will be needed downstream of adsorbers to trap released dust or particles, but care must be taken to allow sufficient area so that freeze up does not occur in the filters. Chemical getters which combine with the more active gases are useful in reducing those contaminants.

After all of these precautions are taken, it will still be very difficult or impossible to say that a J-T valve will not be plugged in a long mission. Also, if power is interrupted, the entire cooler may become filled with gaseous contaminants. These uncertainties require some sort of valve cleaner which can remove the contamination. Mechanical devices have been used for this purpose, but they are risky because they may not totally remove the contamination and they may become stuck. The safest way to clear a J-T valve is to use a defroster. The design of such a device is described in Section 4.

4. Design of a J-T valve defroster

The J-T valve was arranged as shown in figure 1. Cold, high pressure gas passes through the final adsorber where most of the remaining impurities are trapped. The gas enters the thin wall stainless steel tube whose length is shown as ℓ_1, then it passes into the relatively large diameter entry section of the copper J-T valve. The wire passes through the throat of the valve causing this restriction to be ring shaped which reduces the chance of a few particles forming a plug. After expansion at the valve, the gas-liquid mixture passes through the thin wall stainless steel outlet tube, labeled ℓ_2, to the boiler and from there to the low pressure side of the heat exchanger. A resistance heater is wound around the outer throat of the valve. Figure 2 shows a test model of the device.

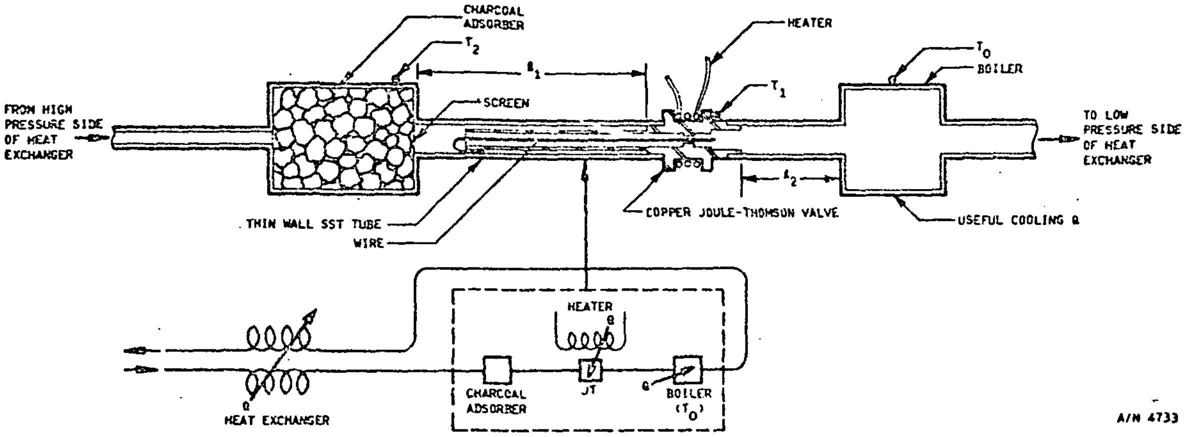


Figure 1 J-T Valve Defrosting Scheme

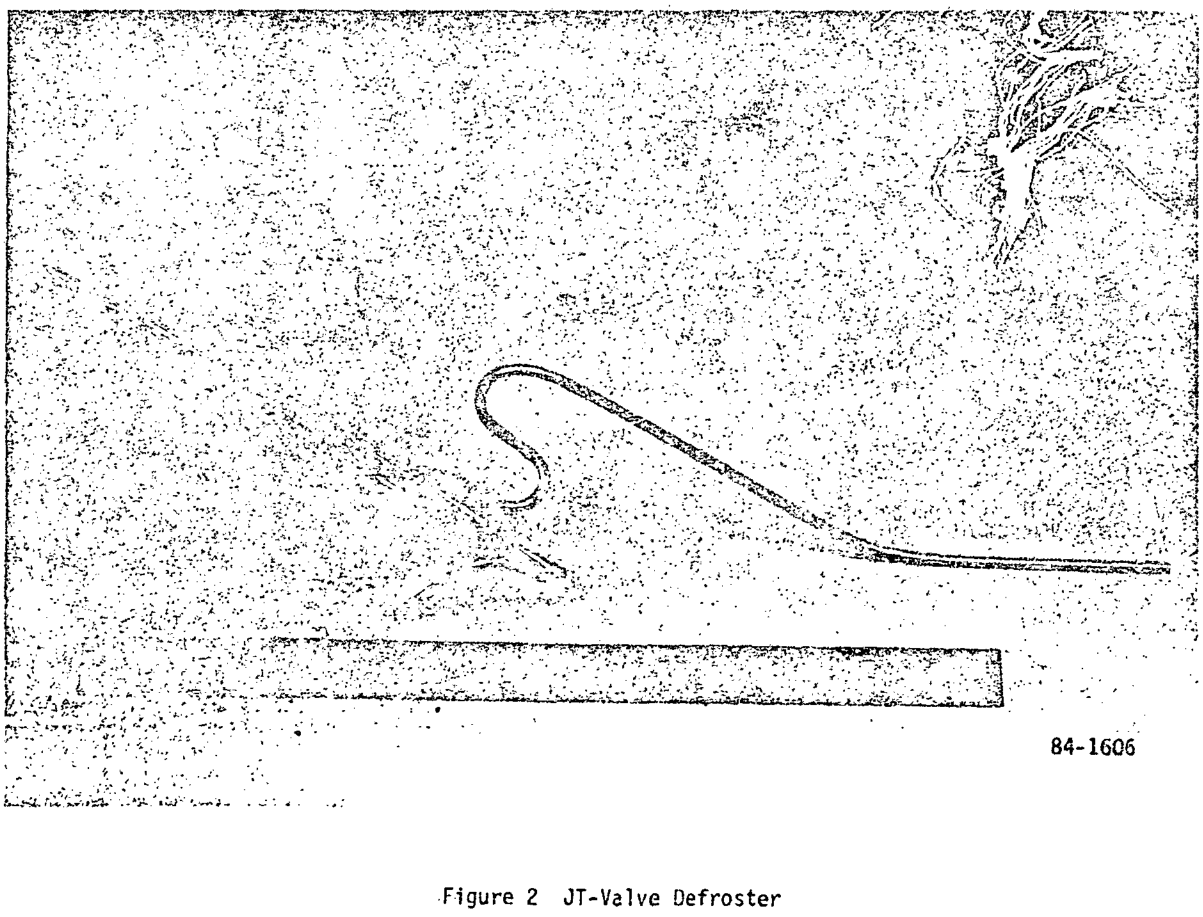


Figure 2 JT-Valve Defroster

The purpose of the arrangement is to allow complete defrosting in a short time period with minimal disturbance to the useful operation of the cooler. The low conductivity stainless steel tubes act as thermal standoffs between the heated copper J-T valve and the adsorber or boiler. This confines most of the heat to the valve where it is needed. Standoff ℓ_1 is also needed to prevent the adsorber from warming up to a temperature where contaminants will be released. The boiler contains a reserve of liquid which maintains constant temperature cooling for the load during the defrosting cycle. The purpose of the copper entry section of the valve is to prevent sudden replugging of the valve after the heater is turned off. This copper part is warmed to room temperature in a few seconds along with the throat of the valve. If the entry section were not there, contaminants from the warm end of the standoff tube ℓ_1 would be immediately available to collect in the valve. As it is, the annular gap between the copper and stainless tubes acts as a cold trap for this temporary source. Further enhancements of this cold trapping scheme are possible but they do not seem to be needed. The heater must be able to raise the valve temperature rapidly to minimize the total heat input to the system and also to the reserve liquid in the boiler.

The heater must also be able to operate over a broad range of heating conditions depending on whether the valve is completely plugged or not plugged at all. This means that the heating power must be several times the steady state cooling power of the cooler because the effective short term cooling power of the stream is high when working against an unplugged warm J-T valve. When the valve is plugged, the same heating power will cause very rapid valve temperature rise because there is no cooling flow, and the heater could burn out. A closed loop heater shut down controlled by valve temperature is needed to handle this range of conditions. Redundancy of heaters and temperature sensors can be provided.

Standoff dimensions, boiler capacity, and heater size are a function of the application. There are considerable differences between 4K Helium valve defrosters and 77K Nitrogen valve defrosters because of the large differences in thermal properties of the materials. To get a feel for the numbers, a 2-watt Nitrogen cooler requires about 20 watts of heating for 10 seconds resulting in a heat input of 200 joules. This consumes about 1 gram of liquid Nitrogen from the reserve in the boiler if precise cooling temperature stability is to be maintained at the load. The heat required to vaporize the plug is negligible and the heat required to warm the copper is only 15 joules. The total heat leak down the standoff tubes is only about 5 joules. Most of the heat goes into the cold gas stream at the valve.

When operated at lower power levels, the defrost heater is also a handy device to control warm up of the system and to aid in initial bakeout. Heating by induction has been suggested as an alternate but this method complicates the power supply for space applications. Section 5 describes the tests performed on the device shown in Figure 2.

5. Defroster testing

Preliminary testing on the J-T defroster (Fig. 2) has been completed for an open-loop Nitrogen J-T system. The results indicate that defrosting can be done in a short time with minimal disturbance to the cooling temperature using low heater input energy. These tests run on our preliminary J-T defroster have been beneficial both in confirming our calculations on the defroster and in defining necessary modifications to the hardware and test methodology.

5.1 Apparatus

The test apparatus, shown in Figure 3, uses K-bottle Nitrogen (ultra high purity) as the source gas. The outer jacket, which houses the coiled tube exchanger and its thermal shroud, is evacuated to 10^{-6} Torr prior to testing. In the 'cold end' of the assembly, there are three thermocouples located and labeled as follows: T_0-potential cooling load (on the downstream mol seive trap), T_1-J-T defroster, T_2-upstream mol sieve trap. The contamination loop inlet is also located in the cold section just upstream of the J-T valve and defroster. A flow meter, temperature scanner, contamination cylinder (H_2O), power supply, voltmeter, ammeter, and pressure controller complete the apparatus.

Note that the system shown in figure 3 makes provisions for the addition of a useful cooling load where the downstream mol sieve trap is currently located. The only load that was applied during these tests was conductive and radiative heat leak.

5.2 Test methodology

In order to develop a J-T defroster that will be able to recover from a variety of worst-case conditions, two concepts required testing. The defroster heater design was tested in order to determine its effect on the overall cooler thermal stability. After sufficient testing and mapping of the defroster's operating characteristics using the pure (ultra high purity) Nitrogen gas source, additional tests were done with a contaminated Nitrogen source. The pure Nitrogen tests are discussed first.

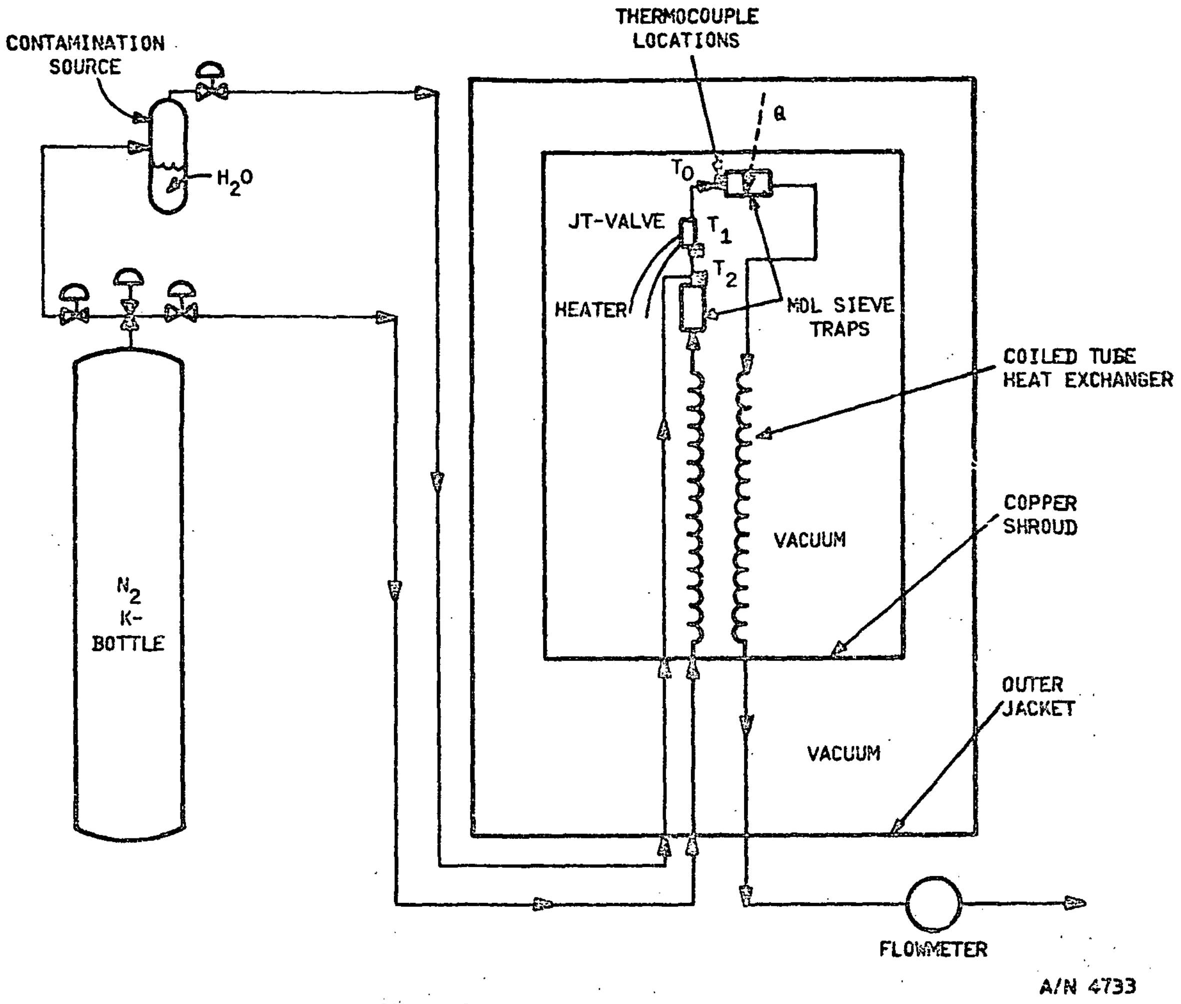


Figure 3 Defroster Test Apparatus

To assure consistency in the pure Nitrogen tests, two variables, the operating pressure (high pressure source) and the time interval between the defrosting, were specified. During the current tests, a source operating pressure of 450 psia provided sufficiently low temperatures at the J-T valve to test the defroster, while still providing the cooling necessary to recover from the defrost. The time interval between defrosting was always less than 2 hours.

When starting a test run, we used a Nitrogen operating pressure of 2000 psia to expedite the equipment cool down by producing high pressure (and relatively high temperature) liquid Nitrogen. Then, over a period of one and a half hours, we gradually decreased the operating pressure until the system was stabilized at 450 psia. Under these conditions the 'cold end' of the apparatus was usually operating under partially flooded conditions. This was apparent when the temperature gradient between the three thermocouples (Fig. 3) was 10K or less. When these conditions were met we tested the defroster.

We powered the defroster heater with a measured voltage while watching the thermocouple attached to the valve, T_1. When the high temperature limit, approximately 20°C, was reached we manually shut off the power supply and recorded the highest temperature observed on the J-T valve. Then we recorded the system response for all thermocouples, flow and vacuum level. The temperature scanner recorded the three temperatures continuously for analysis after completion of the tests.

The contamination loop shown in Figure 3 was used to provide a water saturated Nitrogen source. The contamination loop was used either to provide 100 percent water saturated or partially saturated Nitrogen by using only flow through the contamination source or through the exchanger and the contamination source. When using the contamination source, the source cylinder was heated to approximately 100°C, in order to fully saturate the Nitrogen. The water was expected to freeze out in the J-T valve in a short period of time, as indicated by a reduction in flow rate. Once the flow slowed enough to indicate that the valve was plugged the J-T defroster testing was carried out in the same manner as described for the pure Nitrogen source tests.

5.3 Results

The results for testing done at 450 psia are shown in figure 4, for four separate defrosting tests, case I, case II, case III, and case IV. These tests on the apparatus were done consecutively, during one cool down period. For this reason, we feel that these are the most representative results out of all the tests completed to date. The defrost in case I required 7.6 W and the cooler required 40 minutes before it had stabilized to the conditions prior to the defrost. In case IV, the defrost required 15 W and the cooler returned to the conditions prior to defrosting in only 4 minutes. The heater input power for case I disturbed the thermal stability of the entire cooler ten times longer than the heater input power in case IV. Note that in case I the total energy input is 718 W•s and it decreases to 285 W•s in case IV. The trend can be traced from case I to case IV (Fig. 4).

When the valve is heated, the mass flow is substantially reduced because of the large change in fluid conditions there. This effect reduces the pressure downstream of the valve and results in a lower temperature in the boiler for a short time. This effect would be less noticeable in a cooler with more open downstream plumbing as would be the case for a more refined cooler. There would still be a substantial decrease in flow in a more refined cooler and this would tend to minimize the heat addition due to the defrosting pulse.

The data plotted in figure 5 compare the defroster's requirements in W•s and in equivalent grams of L-N2. This plot is particularly useful design information for the valve tested here, but is only characteristic of this valve. Knowledge of the equivalent grams L-N2 boiled off during defrost cycle allows for the design of a L-N2 reservoir with enough capacity to absorb the entire heat input of the defrost cycle without allowing a change in load temperature.

Defrosting tests run using the contamination loop to simulate a wet Nitrogen source show that the device is effective, but the tests were not entirely conclusive. The loop (Fig. 3) supplies contaminated Nitrogen directly to the system upstream of the J-T valve. However, the valving on the current apparatus allows wet Nitrogen to remain in the contamination tube. Consequently some recontamination would occur before we could take adequate flow measurements to prove that the valve had been totally cleared.

5.4 Conclusions

The tests done using pure Nitrogen confirm that the J-T defroster can be operated with little effect on the thermal stability of the cooler. The current testing equipment must be refined in order to conduct conclusive testing of the J-T defrosting action.

One additional testing problem encountered was the need for better control on the defroster power supply. To protect against heater burnout, the power supply must be automated to shut off the power before the J-T valve temperature exceeds 20°C. An additional thermocouple must be added to the heater very close to (if not toughing) the heater wire in order to more accurately measure the heater temperature.

6. Additional work

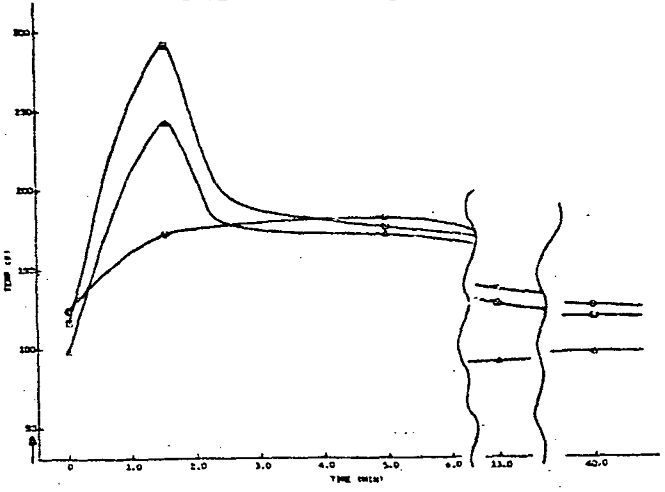
Further refinements of the defroster scheme will be tested in the remainder of 1984 and in 1985. In 1985 we will operate a closed-loop 4K helium J-T cooler employing the defroster and pressurized by a long-life oil lubricated compressor.

The authors are grateful for the ongoing expert consultation of Dr. Tom M. Flynn on various purification concepts and thermodynamic aspects of the J-T cyrocoolers. In addition, Dr. Thomas R. Strobridge has greatly added to our understanding of J-T cyrocoolers by drawing on his 20 years experience with helium liquifiers.

7. References

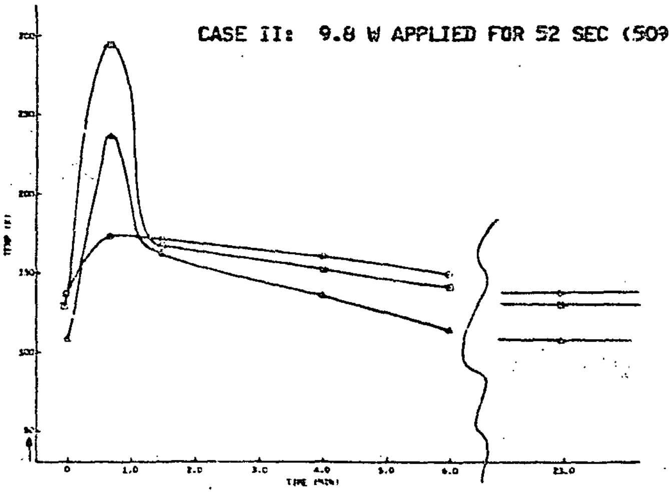
[1] Santeler, D. J., Holkeboer, D. H., Jones, D. W., Pagano, F., Vacuum Technology and Space Simulation, NASA SP-105 (1966).

CASE I: 7.6W APPLIED FOR 1 MIN 35 SEC (718 W-S)



ΔT_0: POTENTIAL COOLING LOAD LOCATION ☐T_1: J-T DEFROSTER ○T_2: UPSTREAM TRAP

CASE II: 9.8 W APPLIED FOR 52 SEC (509 W-S)



CASE III: 11.9 APPLIED FOR 41 SEC (490 W-S)

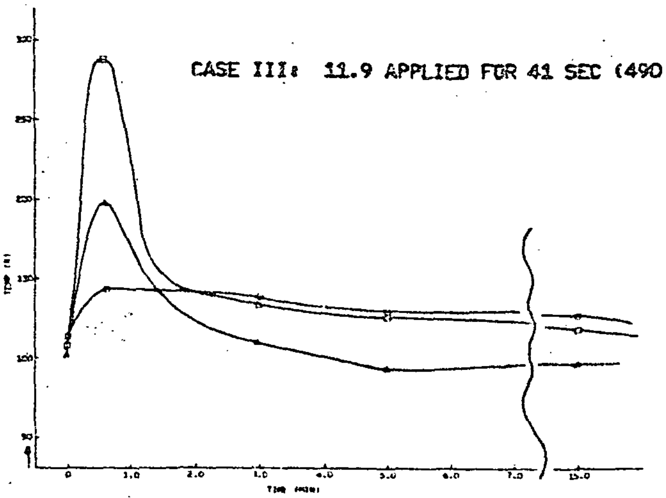


Figure 4 Pulsed Heating of the J-T Cooler (Continued on next page)

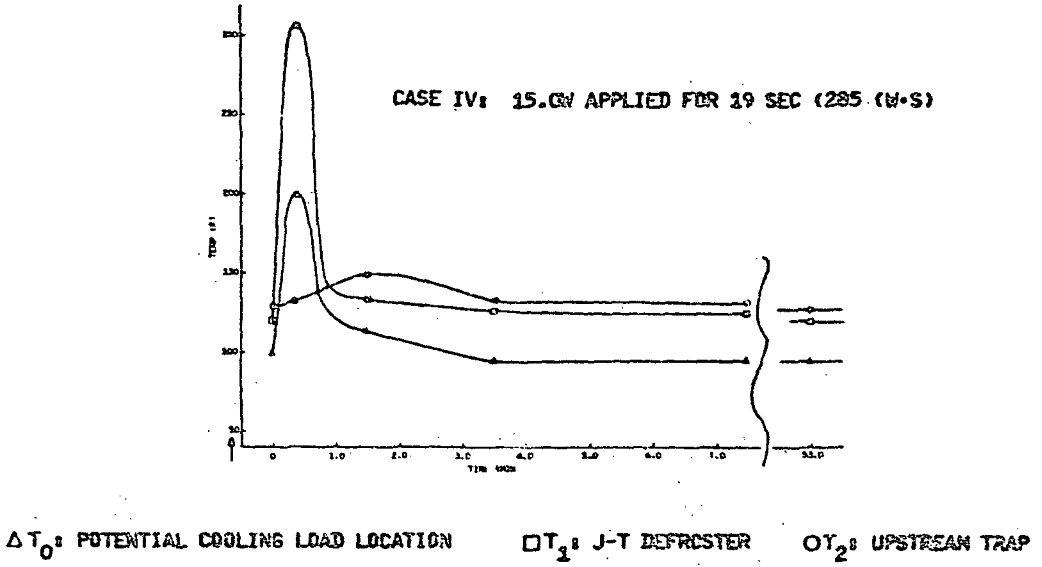


Figure 4 Pulsed Heating of the J-T Cooler

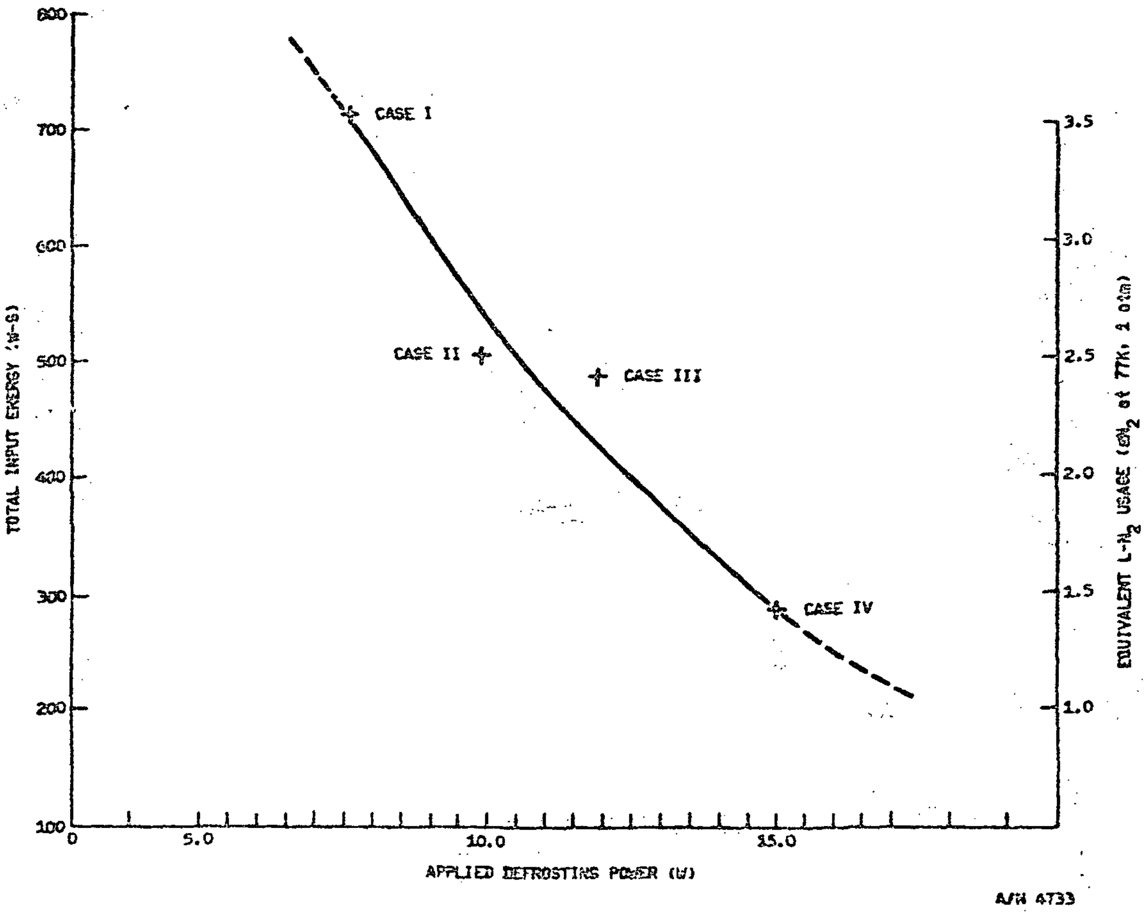


Figure 5 Energy Requirements for Defrosting the J-T Valve (to ~20°C)