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TECHNICAL REPORT RD-AS-91-22

DEVELOPMENT OF A TWO-STAGE ALTERNATE JOULE-THOMSON CRYO-COOLER FOR AAWS-M RISK REDUCTION

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The latest in infrared imaging Focal Plane Array (FPA) technology incorporates Mercury Cadmium Telluride, a material that must be cooled to liquid Nitrogen temperatures for operation. Fast cool–down, within five seconds, has been achieved under a harsh temperature environment (71°C). A Joule–Thomson Cryo–cooler employing two heat exchanger stages has been developed. High pressure Krypton flows through one stage, providing initial pre–cooling, while high pressure Nitrogen simultaneously flows through the other stage. The two–stage gas flow approach along with the superior pre–cooling properties of Krypton enable cool–down under five seconds.

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I. INTRODUCTION

The AAWS–M system, a shoulder–fired fire and forget anti–tank missile, is using the latest in long wavelength staring Focal Plane Array (FPA) technology. This infrared (IR) imaging FPA incorporates Mercury Cadmium Telluride, a material that must be cooled to 80°K in order to obtain the required detector sensitivity in the 8–12 micrometer region.

Current open cycle Joule–Thomson (J–T) cryostat technology allows this temperature to be reached using high pressure nitrogen gas which, when liquified, boils at 77°K. The time presently taken to reach 77°K is extensive. During the interval of time between initiation of coolant and detector cooldown, the system operator (gunner) is on standby.

As a risk reduction effort, MICOM investigated an alternative cryogenic technology. The MICOM objective was to develop a fast cooldown cryostat, with a goal of reaching ≤ 80°K within five seconds under all specified operating temperatures, with hot ambient (+71°C) being a worst case.

Two major tasks were included in this study; a search for an IR transparent gas with superior (better than Argon) cooling properties, and a design optimization for a two–stage J–T cryostat. Krypton has been identified as a highly desirable pre–coolant. It is substantially superior to Argon in cooling capacity, it is inert (safe to handle), and IR transparent (unlike Methane or Freon). A Matrix heat exchanger, demonstrated in a prior effort, possesses a low thermal mass, large heat transfer surface area, and low gas back pressure. Cryostats designed implementing several methods to approach a dual gas system were constructed. Hardware was tested in a dewar that simulated tactical conditions. Final test results demonstrated very statisfactory performance.

II. GAS STUDY

A survey was taken to identify cryogenic candidate compounds to be used as a pre–coolant. Each gas considered had to meet several criteria. The boiling point at one atmosphere must be less than 173°K with less than 103°K desired. Excellent infrared transmission in the 3–5 and 8–12 micrometer range was required, as were safety and long term stability. The gas must be affordable and available. The cryogen must achieve a maximum temperature drop upon free expansion from a gas bottle at room temperature and a pressure of 6000 psi; this is known as the Joule–Thomson cooling efficiency (J–TΔT).

The survey revealed that Krypton gas was most desirable having a J–TΔT of 167°K compared to 67°K for Argon. Krypton has 2.5 times the cooling power of Argon and 5.7 times the cooling power of the primary coolant nitrogen which has a J–TΔT of 29°K. It becomes evident that using a pre–coolant to quickly remove the bulk of the heat load and then allowing nitrogen to bring the detector on down to operating temperatures is the most logical approach to fast cooldown. Krypton has proven to have the best refrigeration capabilities and therefore optimizes this method.

It should be noted that while Krypton performs exceptionally in our two gas, two stage parallel pre–cooler configuration, it cannot be used in the serial pre–cooler configuration. When Krypton is used in the serial pre–cooler configuration, it freezes and blocks the single cooler orifice.

There appears to be no problem with Krypton availability and the price has been extimated to be under $15.00 per missile. In a dual stage pre–cooler configuration, the Krypton quickly reduces the primary coolant nitrogen's temperature. The Nitrogen gas, still at high pressure but now at a much colder temperature has a greatly improved Joule–Thomson efficiency. This dual stage configuration was the final optimized form of the cooler.

III. DEWAR DESIGN AND CONSTRUCTION

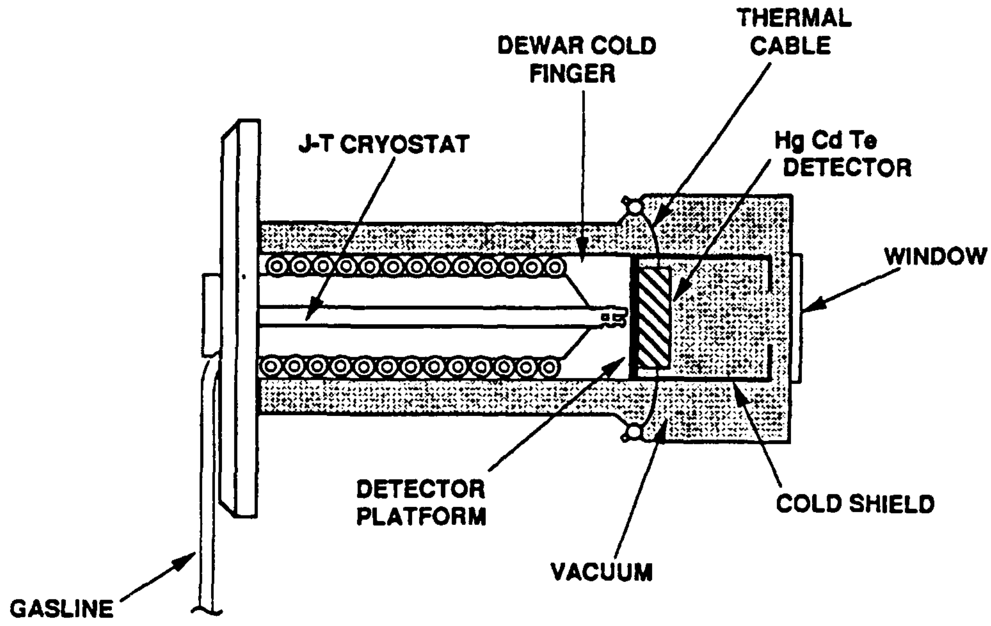

Figure 1. Existing Detector/Dewar Package.

A. Joule Mass

In order to insure fast cooldown, the design of the dewar should minimize the thermal mass of the sensor system. The thermal mass refers to the initial heat load that the cryostat must remove from the system. The various components of the detector/dewar system and their contributions to the joule mass are shown below.

Detector Cold Shield	30%
Dewar Cold Finger	30%
Detector Platform	32%
Detector	7%
Mounting Adhesive	.5%
Thermal Cable	.5%
TOTAL JOULE MASS	100%

B. Steady State Heat Load

Once the initial heat load has been removed from the system, which implies a cooldown state has been reached, the detector will tend to warm at a rate proportional to the steady state heat load of the system. The cryostat must be continuously supplied with high pressure gas to keep the detector at operational temperatures. At this point, a high gas flow is no longer necessary because the thermal mass has already been removed from the system and only a sustain type operation is needed. A control mechanism attached to the cryostat orifice will reduce flow rate to the lower value required.

The thermal leakage due to the quality of the vacuum on the dewar determines the continuous heat loading value. Once the dewar vacuum has been optimized the factors below become the main contributors.

Thermal Conduction from Dewar Cold Finger	64%
Thermal Radiation from Dewar Cold Finger	16%
Thermal Radiation from Thermal Cable	20%
TOTAL STEADY STATE HEAT LOAD	100%

C. AAWS–M Test Dewar

With data supplied by the system prime contractor, a dewar was constructed that incorporated the joule mass and steady state heat load associated with the AAWS–M system. This test dewar was used to determine cooldown time, run time, and temperature stability of each cryostat developed.

A thermocouple mounted on the inside base of the dewar cold finger senses the liquid cryogen temperature. The test is set up in an environmental chamber which can provide testing at specifed hot and cold temperatures outlined in the system specifications. An actual AAWS–M test dewar was subsequently used in our final acceptance testing.

IV. CRYOSTAT DESIGN AND CONSTRUCTION

A. Finned–Tube Heat Exchanger Technology

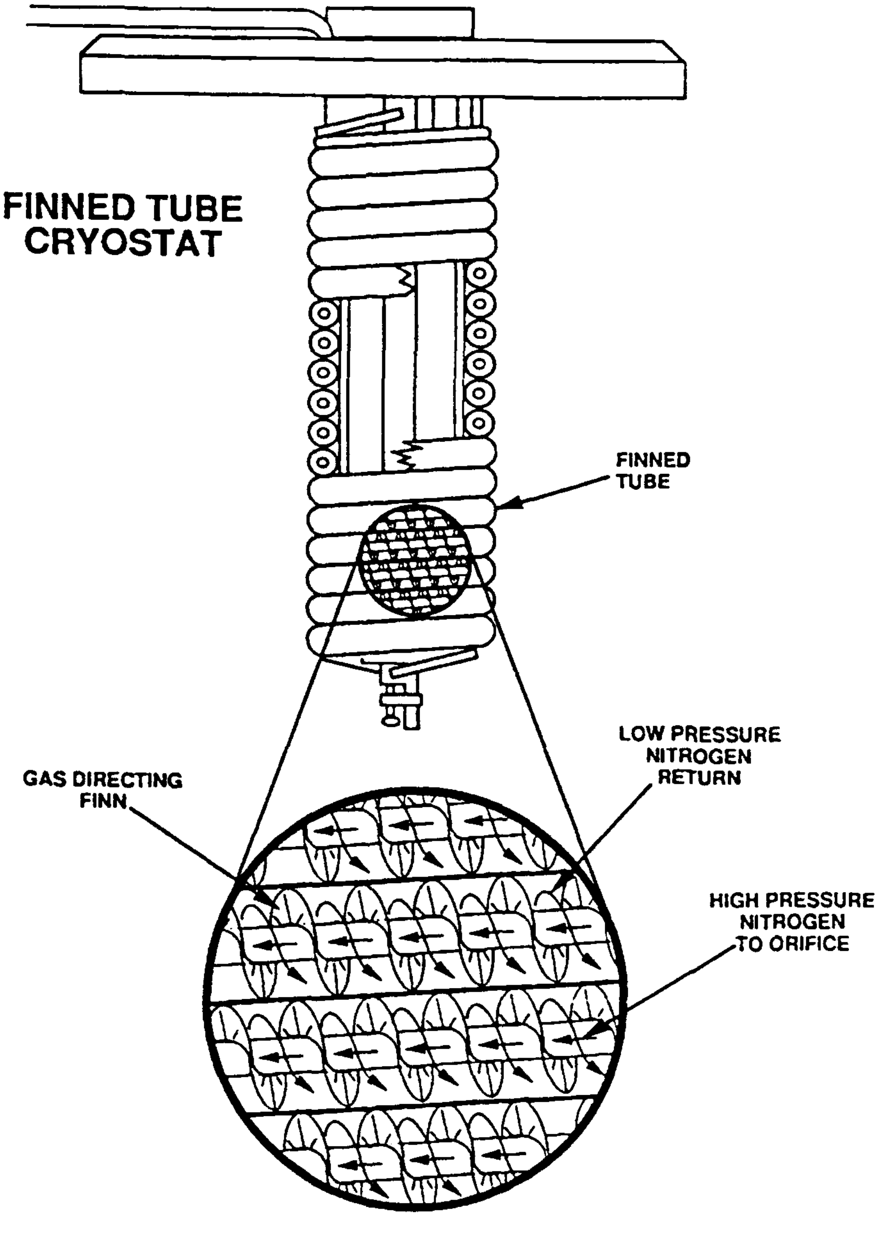

Figure 2. Finned Tube Cryostat.

The Finned–Tube Technology is the most commonly used in fast cooling J–T cryostats. A continuous fin is spirally mounted to the outside of a small high–pressure gas line. The fin will spiral up the length of the line, with the line wound in a helix around a sleeve. The end of the finned–tube line is connected to the orifice located at the tip of cryostat. When the cryostat is inserted into the dewar the orifice will be positioned at the base of the dewar cold finger. As the high pressure gas exits the orifice, the expanded gas is forced to travel along the finned tube. The expanded gas is at a very low temperature and as it flows up the finned–tube it spirals around the high pressure gas line, pre–cooling the incoming gas before it reaches the orifice. It has long been known that cooling the high pressure cryogen prior to expansion to low pressure will increase its refrigeration capability. The regeneration concept boosts the efficiency of the cryostat aiding fast cooldown but in fact is an inherent necessity for the J–T process to function. After the expanded gas has run its course through the cryostat, it exits the base where the finned–tube line began.

B. Matrix–Tube Heat Exchanger Technology

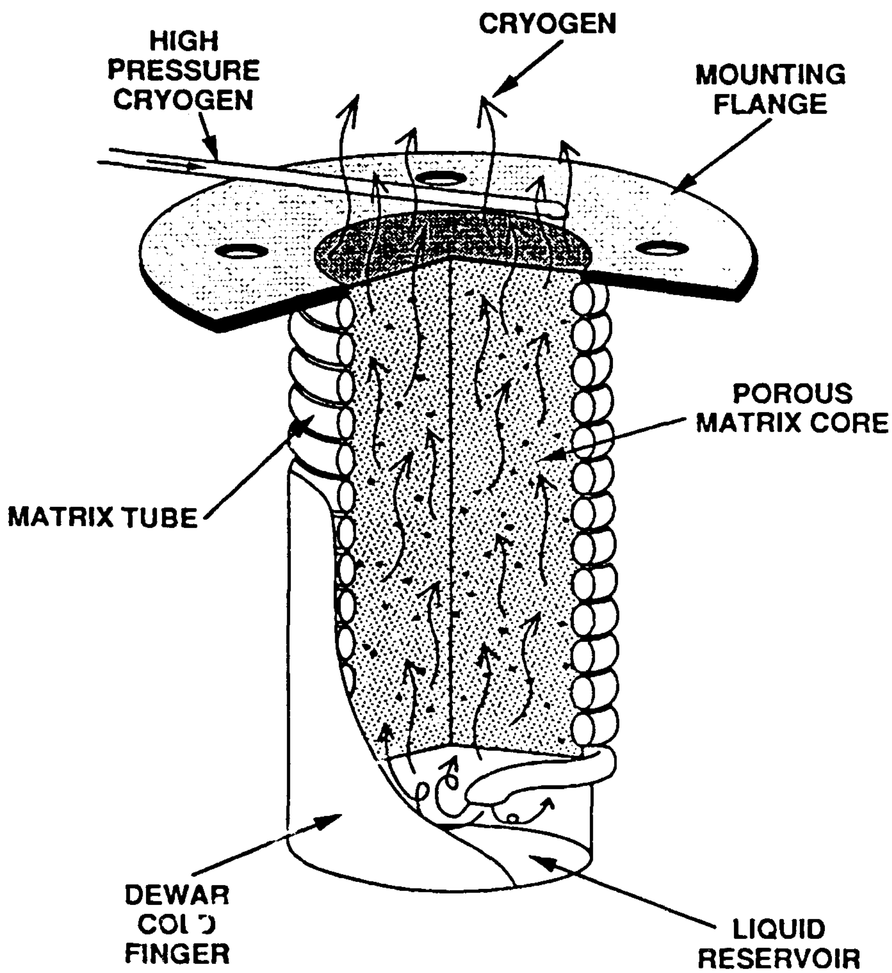

Figure 3. Matrix Tube Cryostat.

In the matrix–tube heat exchanger technology, we replace the cryostat cold finger with a highly conductive, low mass, large surface area porous material. Around the porous material, a high pressure gas line is wound and bonded. The gas line is attached to an orifice at the base of the porous material. Once the matrix–tube heat exchanger is placed in the dewar, the low temperature expanded gas will cool the detector as before, but will then flow out through the pores, cooling the material. The thermal bonding of the high pressure line to the porous core allows for quick pre-cooling of the high pressure gas flowing into the orifice.

A feature of this heat exchanger design is the very low back pressure induced in the out-flowing gas, particularly as compared to the doubly circuitous lengthy path of the finned-tube design. This allows a greater coolant flow at lower back pressure, which provides both greater cooling capacity and faster cooldown.

C. The Control Mechanism

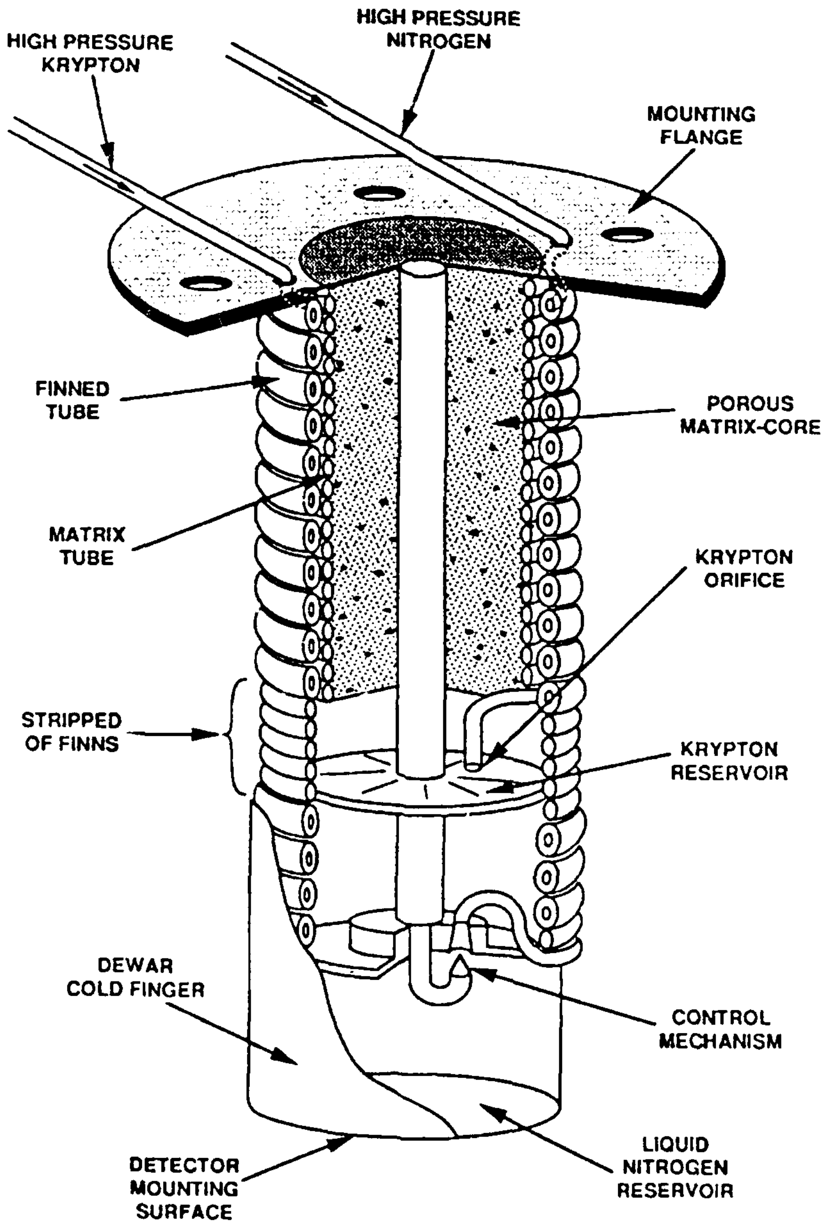

Figure 4. Two-Stage Alternate Cryostat.

Fast cooldown requires that the gas flow rate be at maximum during the initial cooldown stage when the thermal mass is being cooled. Once the thermal mass has been stabilized the high flow rate is no longer needed to maintain operational termperature. A control mechanism can reduce the gas flow rate once the cryostat and dewar have reached the proper temperature. This will conserve the gas supply and allow the detector to remain in a cooldown state for a longer period of time.

The control mechanism is made up of a material that contracts when cooled. This material is attached to a needle that is positioned adjacent to the orifice. As the temperature is lowered the material draws the needle into the orifice partially blocking the opening thus reducing the gas flow. This process is self–regulating and several mechanizations are commonly employed in many coolers.

D. Parallel Heat Exchanger Combination

Test results demonstrated that having the pre–coolant and the primary coolant run simultaneously through independent heat exchangers had significant advantages over running them serially through the same heat exchanger. Cryostats were developed which contained two heat exchangers, one inside the other. Testing several crysotats produced a configuration containing the matrix–tube as the inner and the finned–tube as the outer heat exchanger, which gave the best results. In this configuration, the pre–coolant would run through the inner matrix–tube cryostat and the primary coolant would run through the outer finned–tube cryostat simultaneously. This would allow the inner heat exchanger to quickly remove a large percentage of the dewar thermal mass as well as pre–cool the primary coolant, Nitrogen. During this time the primary coolant, a poor refrigerant by the pre–coolant's standard (but greatly improved by being pre–cooled), would flow through the outer heat exchanger further cooling the detector to operational temperatures due to its lower boiling point.

E. Two–Stage Sequential Gas Flow Operation

High pressure Krypton begins flowing within the inner matrix tube heat exchanger. The gas undergoes a pressure drop from 7200 psi to roughly 15 psi as it exits the orifice. No control mechanism is needed here because the Krypton will quickly be exhausted; its purpose is pre–cooling only. The expansion absorbs most of the system's initial heat load.

The expanded gas flows out through the porous matrix core, cooling the core and the gas line that has been bonded to it. As the gas continues to flow the temperature drops down to the boiling point of Krypton (116°K), liquid Krypton begins to form, pooling within the inner reservoir. The dual function of the inner matrix tube heat exchanger is to cool the dewar system from room temperature (295°K) to liquid Krypton temperature (116°K) in one sixth of the time it would have taken the nitrogen alone and to pre–cool the incoming Nitrogen. Thus far, the system has not been cooled beyond the pre–coolant boiling point.

The outer finned–tube heat exchanger, using high pressure nitrogen, has the task of cooling the system from 116°K to the 77°K necessary for detector operation. Beginning operation simultaneously with the Krypton, Nitrogen will undergo the same pressure drop as before with the expanded gas traveling back up a shortened finned–tube line furthur pre–cooling the incoming gas that has already been greatly pre–cooled as the inner cryostat operation becomes effective. As stated before, pre–cooling the high pressure gas prior to expansion increases the efficiency of refrigeration. This technique is further employed by striping the fins off the high pressure tubing in the area adjacent to the Krypton reservoir. With thermal impedence at a minimum the liquid cryogen can quickly pre–cool incoming Nitrgoen. With the crysotat inserted within the dewar cold finger, the base of the dewar becomes the reservoir for liguid Nitrogen. The detector, mounted on the underside of the dewar cold finger, is thermally coupled to the liquid. The control mechanism is set to contract and begin pulling the needle into the orifice at a specific temperature (near 100°K), thus reducing the nitrogen flow rate after cooldown.

V. TEST RESULTS

The alternate cryostat was evaluated in three independently developed AAWS–M dewars. Cooldown curves 1 and 2 were produced when the cryostat was tested in the APD Cryogenics dewar. Cooldown curve 3 from a Santa Barbara Research Center developed dewar and cooldown curves 4, 5, and 6 from a Texas Instruments developed dewar.

During development of the alternate cryostat, APD Cryogenics constructed an AAWS–M test dewar to evaluate their designs against the system's thermal environment. Tests confirmed cooldown to 82°K in 2.5 seconds from room temperature 24°C (curve 1) and to 82°K in 4.0 seconds from high ambient 71°C (curve 2). The large spike seen in the cooldown curve denotes a change in temperature scale. At the top of the spike, the vertical temperature scale shown begins.

The Santa Barbara Research Center in their work on the AAWS–M program developed a test dewar. Testing of the alternate cryostat within this dewar showed cooldown to 82°K in 3.8 seconds from room temperature 24°C (curve 3).

Texas Instruments has developed a cryostat test station in which the current AAWS–M cryostats (developed by Carlton Technologies) are evaluated. This station contains the latest in their test dewar technology. Tests of the alternate crysotat in this station showed cooldown to 82°K in 3.1 seconds from low ambient -20°C (curve 4), cooldown to 82°K in 5.52 seconds from room temperature 24°C (curve 5) and cooldown to 82°K in 6.86 seconds from high ambient 71°C (curve 6). In these plots, the first five seconds have been expanded to show cooldown detail.

VI. CONCLUSIONS

1. Cooldown in 2–6 seconds has been demonstrated, including a worst case hot environment.
2. Sequential dual gas flow through a dual stage cryostat is the key to this success.
3. Discovery of Krypton as a pre–coolant is a significant factor.
4. Krypton is available and affordable.
5. Krypton is not usable in dual gas serial coolers due to freeze up blockage of the primary (in this case only) expansion orifice.
6. Final design operated in a Texas Instruments AAWS–M test dewar. Under a worst case condition, cooldown time to 82°K was achieved in 6.86 seconds. Cooldown time can be furthur improved if the alternate cryostate performance were optimized in a test dewar containing all piece parts along with a FPA coldshield such as the ones used during tests at TI.
7. Substantial improvement has been demonstrated in two areas:
   a. 1/4 to 1/5 the cooldown time of present cryostats.
   b. Immediate re–cool capability (versus 30 seconds or more) when a BCU is replaced, due to the parallel pre–cooler which is not inhibited at a cold start as is the serial Argon pre–cooler.

These two improvements should make this a very desirable product improvement for the system.

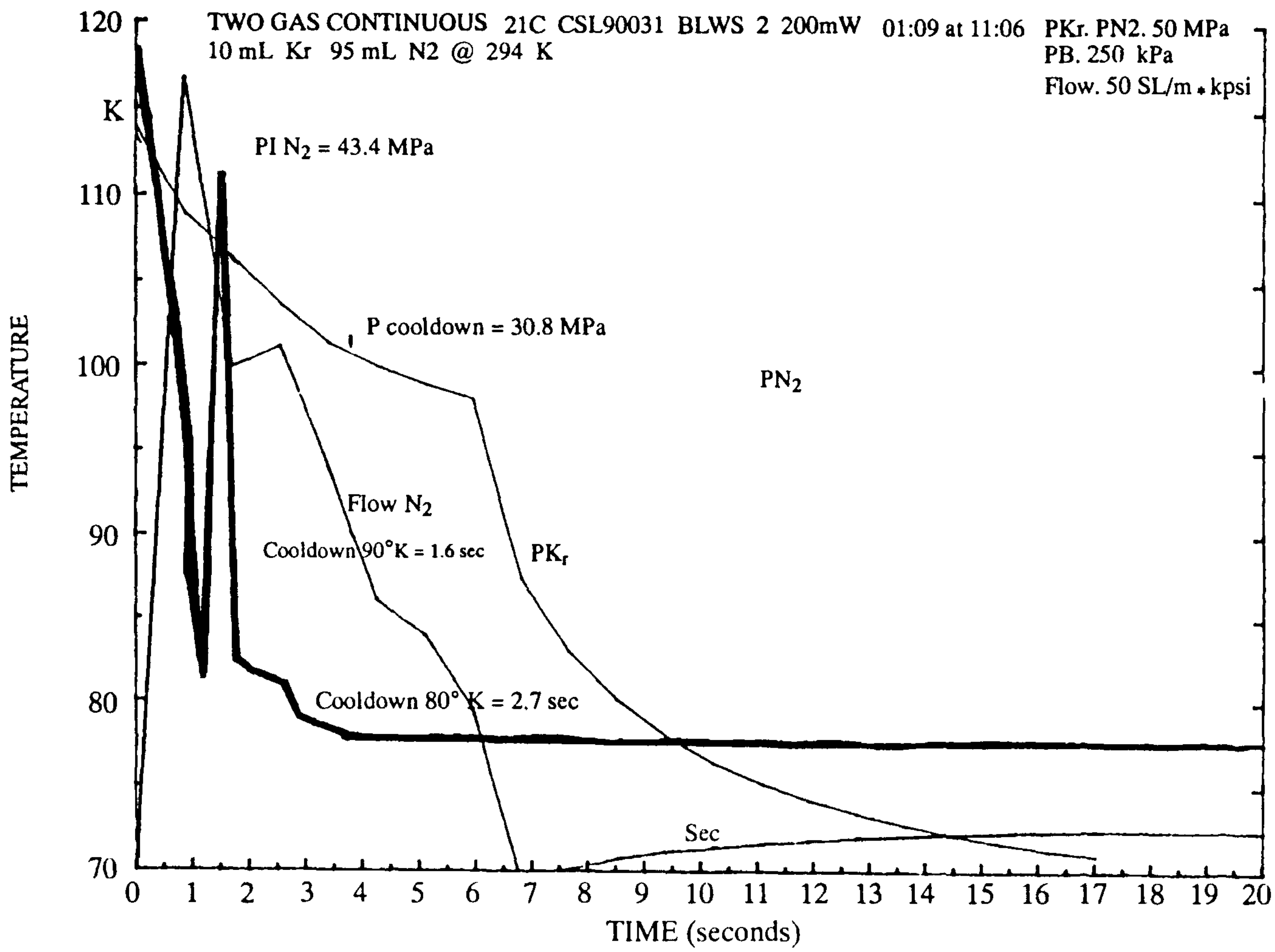

Figure 5. Cool–down Curve 1, Room Temperature with APD Cryogenics Dewar.

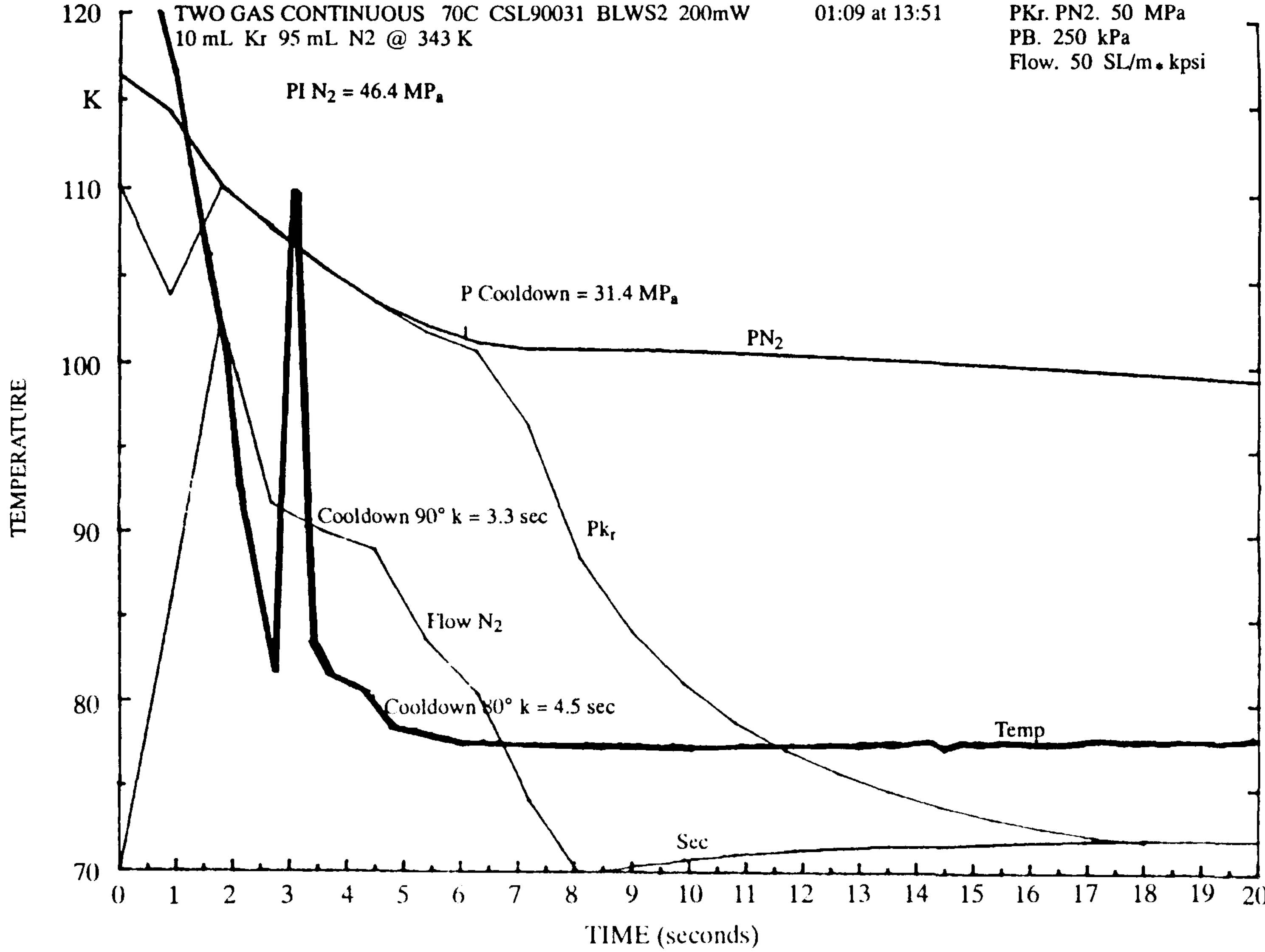

Figure 6. Cool-down Curve 2, High Ambient with APD Cryognenics Dewar.

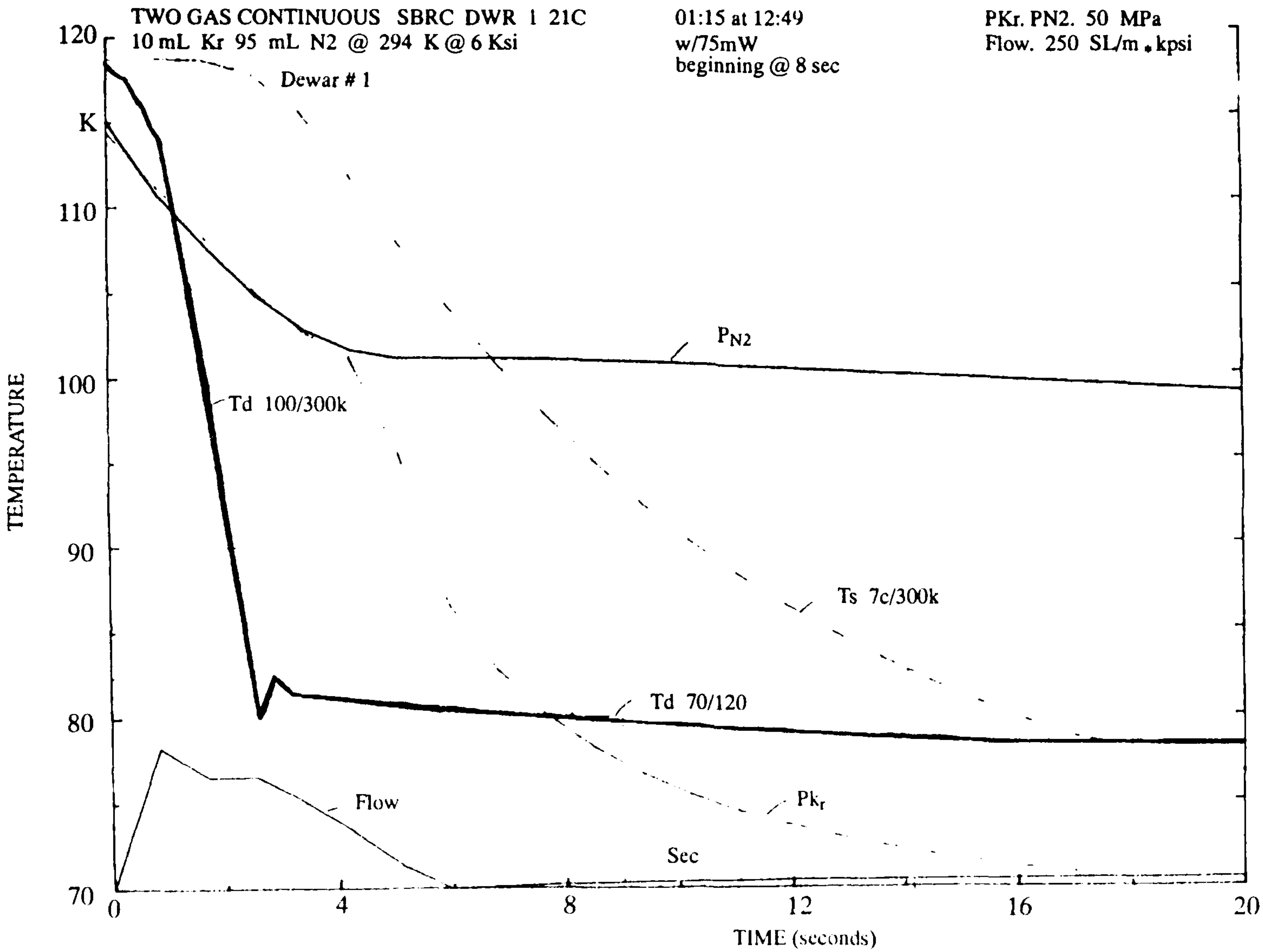

Figure 7. Cool–down Curve 3, Room Temperature with Santa Barbara Research Dewar.

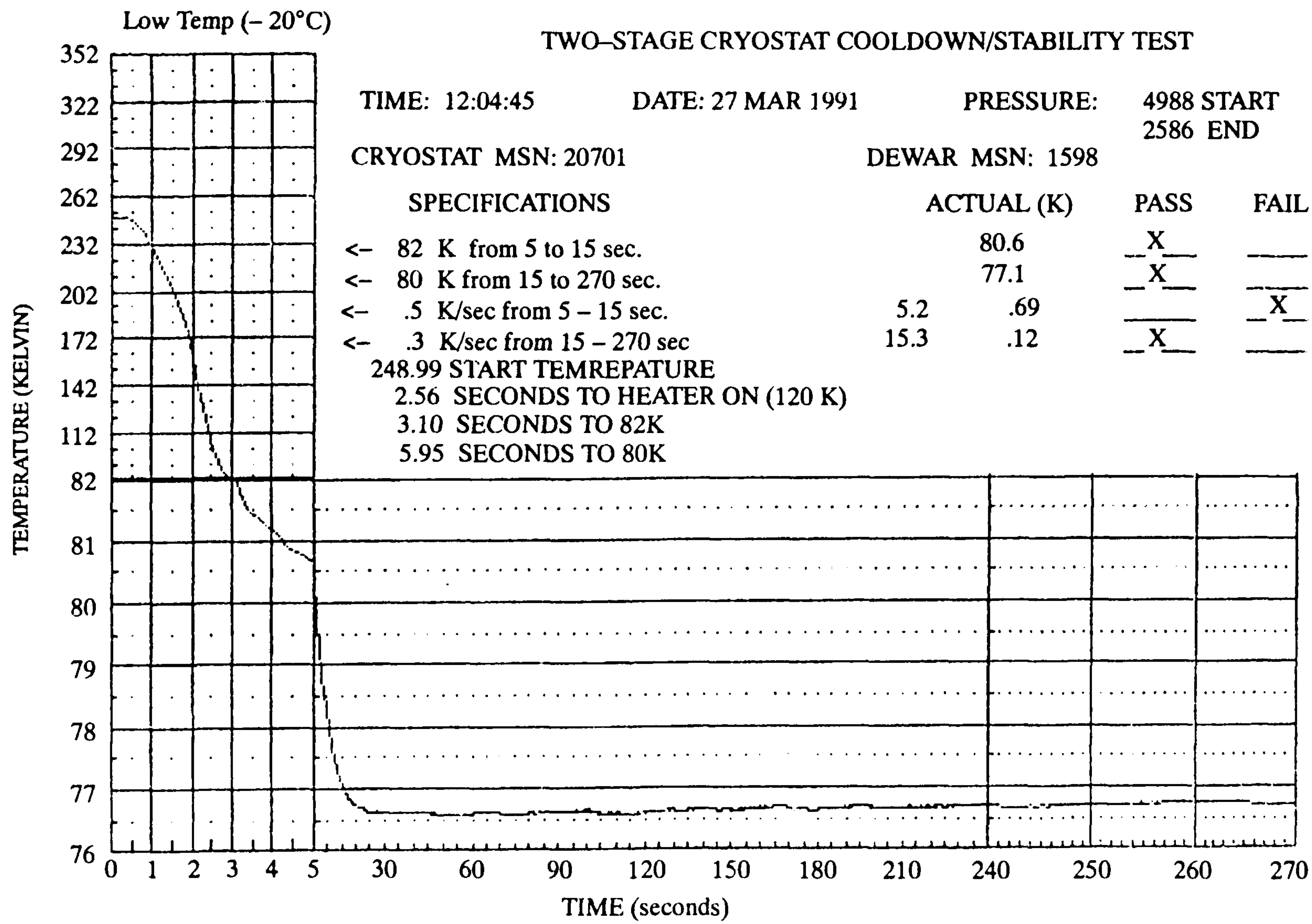

Figure 8. Cool–down Curve 4, Low Ambient with Texas Instruments Dewar.

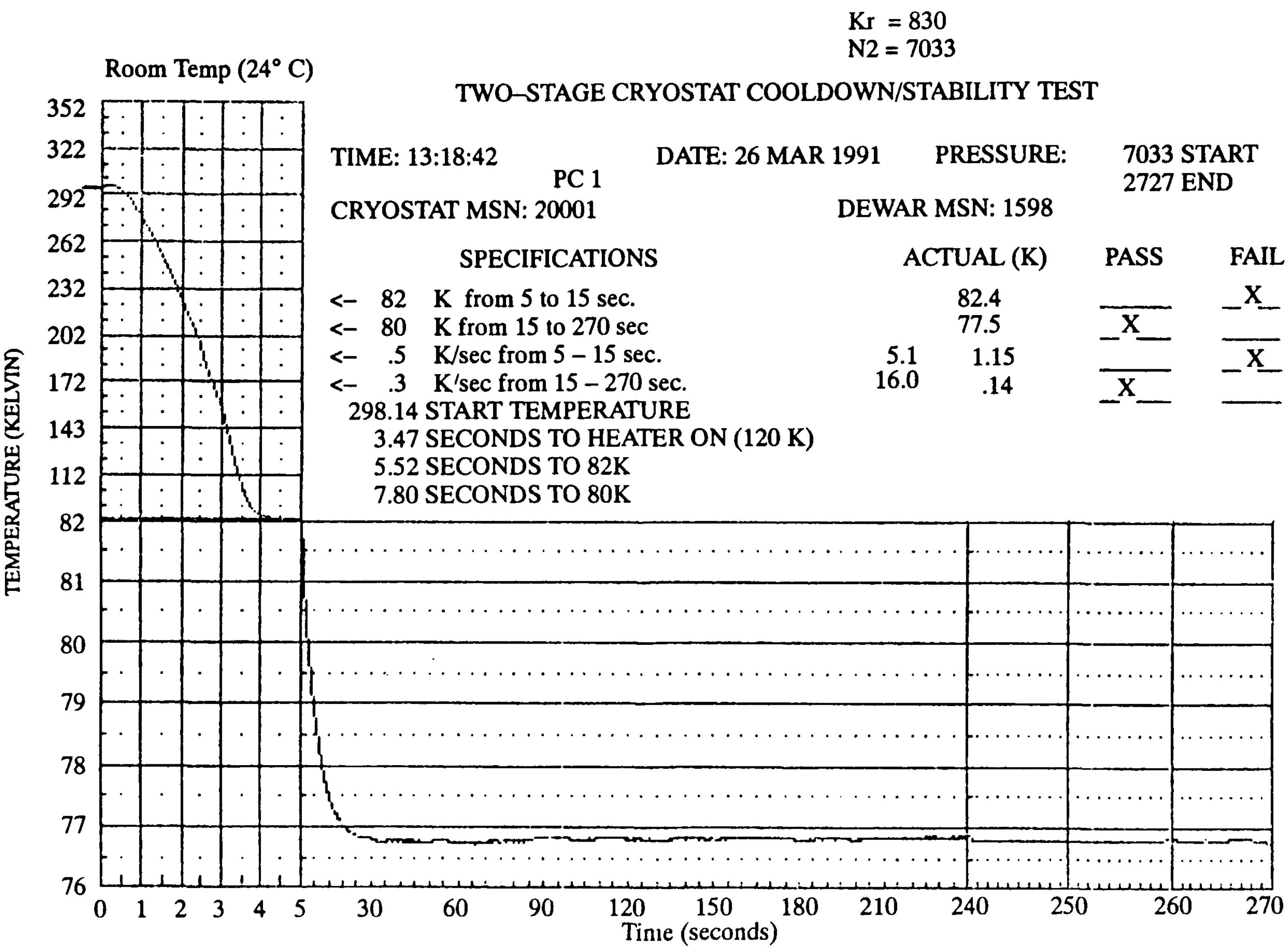

Figure 9. Cool–down Curve 5, Room Temperature with Texas Instruments Dewar.

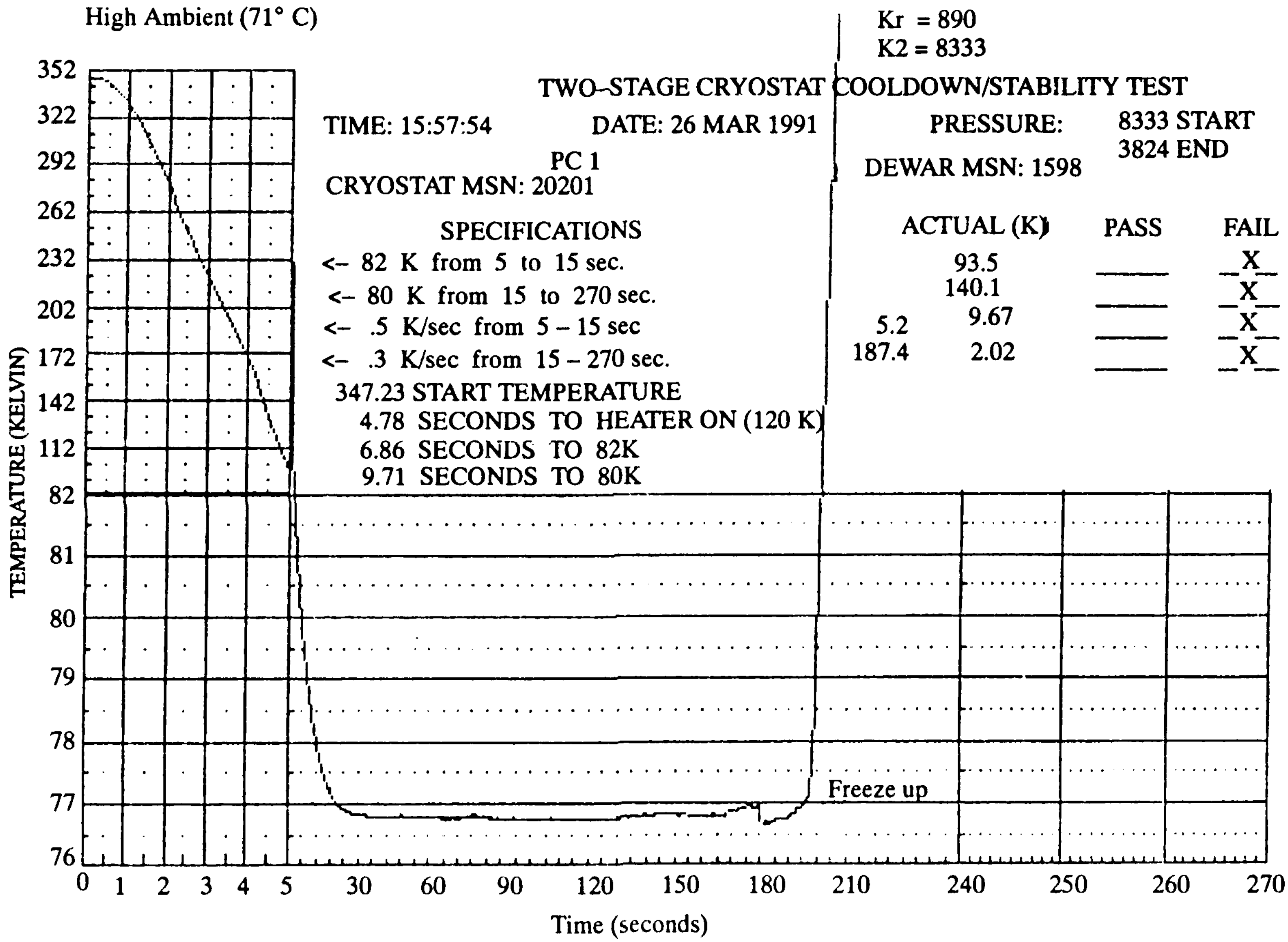

Figure 10. Cool–down Curve 6, High Ambient with Texas Instruments Dewar.

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