N95- 14085

REFURBISHMENT OF A 39' THERMAL VACUUM CHAMBER

Arthur A. Edwards
Space Systems/Loral
Palo Alto, California

ABSTRACT

The 39' thermal vacuum chamber at Space Systems/Loral in Palo Alto, California, was built by CVI Corporation in 1969. Since then, it has been used to test numerous spacecraft including those of the GOES, Intelsat, Insat, Superbird, N-Star, NATO and other programs. Ten years ago, the aluminum LN_2 shroud experienced serious fatigue failures in the field welded jumper tubing, effectively shutting down the chamber for vacuum testing. (Refer to a paper presented by A. Edwards in 1984 at the 13th Space Simulation Conference titled **Fatigue Induced Cracking in Aluminum Shroud of 39 Foot Vacuum Chamber**). The problem was repaired at the time, but new failures began to reappear a few months ago and are now occurring at a rate that suggests that the shroud may again become inoperable. Consequently, Space Systems/Loral is spending in excess of $6 million to replace the shroud and the existing LN_2 equipment with a new, state of the art cryogenic system.

In May, 1994, a contract was awarded to PSI, Incorporated, to remove the existing shroud and LN_2 pumping system and replace it with a gravity fed shroud and distribution system. Included in the contract are eight skid mounted gaseous nitrogen pumping systems capable of controlling shroud zone temperatures between +150°C and -180°C. The project is scheduled to be completed in April 1995.

HISTORY

The SS/Loral thermal vacuum chamber is a top loading 39 foot sphere with a subcooled, pressurized LN_2 system feeding an aluminum shroud (figures #1 and #2). The shroud is interconnected with jumpers in a series/parallel combination that separates it into six zones (figure #3). The liquid flow is large enough and the pressure high enough that the LN_2 remains as liquid throughout the shroud, vaporizing the secondary liquid when it reaches the subcooler's heat exchanger. The advantage of the system is that is does not vapor lock with the thermal loads up to 300 KW. One of its disadvantages is that the pumps required to maintain this high pressure/flow rate introduce energy into the liquid which ends up as consumed LN_2. In addition, the liquid temperature is relatively high, because heat is absorbed by the LN_2 through a sensible process resulting in an increase in the liquid temperature as it travels through the shroud.

In 1984, the shroud's interconnecting jumper tubing began failing during each pumpdown cycle through a fatigue fracture mechanism that is explained in detail in the proceedings of the Space Simulation Conference held in Orlando that year. Many of the field welded jumpers were replaced, effectively stopping the failures. Since then, SS/Loral has successfully tested many spacecraft in the chamber, and the shroud has held together satisfactorily. However, during the past few months, fatigue failures have been occurring in tubing that was not replaced ten years ago. The failure rate has increased enough to indicate that something should be done to correct the problem before the chamber is once again unusable. The problem is compounded by the fact that SS/Loral has eleven thermal vacuum tests scheduled in the chamber during 1994 and 1995. To work around this situation, a plan has been devised to accomplish the refurbishment without disrupting the testing schedule.

COURSE OF ACTION

It is obvious that the present shroud repair program is not a long term answer to the problem. A permanent solution had to be found. It was decided to remove and replace the entire shroud rather than repair it as it failed. Process Systems International of Westborough, Massachusetts, was selected to accomplish the refurbishment, and, together with SS/Loral, devised a plan to remove the existing system and replace it with a new shroud that will not experience fatigue failures. The new shroud will be supplied with a gravity fed LN_2 system that will provide the liquid flow required to handle a maximum 200 KW heat load at the lowest possible LN_2 consumption.

In addition to its LN_2 capability, each of the shroud's six zones can now be operated independently at any temperature between $+150^{o}C$ and $-180^{o}C$. A new 48" gate valve and roots blower will also be added to the vacuum system to reduce pumpdown time. In addition, all the new LN_2 piping will be vacuum jacketed. To operate this equipment, a computer controlled operating console will be provided.

SCHEDULE

The chamber testing schedule for the next two years was a serious concern to SS/Loral in its decision to approve this project. Because of this schedule, it appeared that there would not be sufficient time to replace the shroud within that period. During the initial design contract, however, the two companies worked together to develop an assembly and installation program that will allow the refurbishment project to be accomplished without interfering with testing. To do this, the installation sequence was separated into three phases:

> **Phase 1** - That work which can be accomplished at any time without regards to chamber activity.
> **Phase 2** - That work which can be accomplished between any early vacuum tests.
> **Phase 3** - That work which can only be accomplished in a period between satellite vacuum tests. This work cannot be stopped or postponed once it has started, and, if delayed, will delay the following spacecraft vacuum tests accordingly.

Scheduling of the work in the first two phases is not critical, and can be easily accomplished with good planning. The work associated with the third phase, however, is another matter. The third phase work includes such projects as removing the existing shroud, cutting penetrations through the chamber wall, installing the new LN_2 distribution system, installing the new shroud, removing the existing and installing the new operating console and interconnecting all of the new piping and electrical wiring. It is critical that the third phase work be accomplished within the openings of the existing test schedule. No delay in spacecraft testing can be tolerated.

Fortunately, SS/Loral's testing schedule shows a two month window between tests early in 1995, which is one of the few major breaks that will occur within the next two years. Consequently, PSI and SS/Loral developed an installation program that would fit into this window. The typical span to accomplish the amount of work in phase three has been as long as four months in previous projects. However, PSI and SS/Loral engineers worked together to develop a plan that will allow the phase three work to be accomplished in the two month span available.

The essence of this plan is the pre-assembly of all the major components before the installation begins. For example, the new LN_2 shroud will be assembled into six structurally self supporting segments, assembled and leak checked on the high bay floor. When the window opens up, and the old shroud is removed, the segments will be set into the chamber and connected to their supports. No tubes will be welded inside the chamber, the final piping connections will be made with flexible cryogenic couplings. The GN_2 and LN_2 pumping skids will be assembled in PSI's shop and shipped ready for installation. This pre-assembly includes as much of the wiring and piping as possible. The new operating console and all of the vacuum jacketed LN_2 piping will also be pre-assembled and ready for installation. When the window opens, several teams will work in parallel to install the various components and systems within the two month span allotted. The success of this plan will be in the hands of PSI's site engineer and his installation teams, and will depend on the coordination efforts of the two companies.

OPERATING COST CONSIDERATIONS

The operating cost of a thermal vacuum test chamber is very much dependent upon the thermal cycle of its LN_2 system. A typical thirty day thermal vacuum test in a chamber using a subcooled nitrogen system can cost as much as $150,000 in LN_2 consumption alone (at $.30 per gallon). This adds up to close to $1 million per year. Obviously, a reduction in LN_2 consumption can result in significant cost savings over a span of several thermal vacuum tests. Consequently, considerable thought was given to minimize the new system's LN_2 consumption. To accomplish this goal, the existing pressurized, subcooled system was abandoned and a gravity fed design was adopted. Basically, the system works like a ship's steam boiler. A large header is connected to the bottom of the shroud's vertical section from which the liquid flows vertically through finned tubing into a collection header attached to the top of the shroud. There is little LN_2 pressure, so its temperature is as low as possible. As the shroud is radiated by the heating rods or lamps (at a one sun maximum density), bubbles of GN_2 are formed inside the tubes and the heat is absorbed as latent thermal energy. These bubbles travel up the tubes and are collected in the top header and then returned, along with excess LN_2, to a separator tank. This

a-4.

design maintains two phase (saturated) flow throughout the tubing, so that no part of the shroud is exposed to superheated gas or becomes vapor locked. This is accomplished by designing the liquid flow through the shroud tubes to be twenty times that of the LN_2 that is vaporized. A pump is not needed to accomplish this because the pressure difference between the liquid supply head and the partially vaporized return head is sufficient to circulate adequate liquid. The result is an effective cryogenic system, operating at the lowest possible temperature at a minimum LN_2 consumption rate.

To supplement the main shroud system, twelve auxiliary LN_2 zones are included to provide cooling to individual spacecraft components as required for each test. Because of the pressure drop and horizontal configuration in these zones, an LN_2 pump is used to transfer the liquid through these auxiliary zones.

SYSTEM DESIGN

The new LN_2 shroud has approximately 3600 square feet of area and will be built in three segments, a top, bottom and cylindrical segment. Figure #4 shows a cross section of the three and their location in the chamber. The cylindrical segment is divided into four zones and the top and bottom segments are each a single zone. Each cylindrical zone will be fed from its own 300 CFM GN_2 skid. The top and bottom segments are constructed of vented extrusions connected to intermediate headers (figure #5). The top segment is 800 square feet and the bottom segment is 1000 square feet and each segment will be fed by its own 650 CFM GN_2 skid. To prevent vapor lock, there are no horizontal flow paths anywhere in the shroud. The cylindrical section is constructed of PSI's extruded tubing number HIV-42 at 7.5 inch centers as shown in Figure #6. The tubes are connected to a supply header at the bottom and a return header at the top (figure #7). All the vertical tubes are in parallel and there are no interconnecting jumpers in the shroud. This configuration is important because it eliminates the possibly of the fatigue failure problems that SS/Loral has experienced with its pressurized shroud. The side wall tubing with its overlapping fin design ensures optical density while providing a molecular conductance of 160 liters/sec.ft^2. With a side wall surface area of 1800 square feet, the total conductance through the cylinder is 290,000 liters/sec. All shroud sections will be fabricated from 6000 series aluminum.

Since there are no pumps in the LN_2 system, the key to its design is the driving force that is caused by the static head from the LN_2 separator tank. This tank is fed directly from the main LN_2 storage tank as demanded by a level sensor. The liquid is then fed to the shroud from the separator through a vertical supply header that enters the chamber near the bottom. After the LN_2 travels up through the shroud, it collects in the return headers and is routed back to the separator. There, the gas is vented and the liquid is returned to the shroud.

If no heat were introduced into the LN_2 throughout this cycle, there would be no liquid flow because the supply static head would be equal to the return static head. But heat is introduced into the liquid through heat leaks and through thermal energy directed onto the surface of the spacecraft. This heat load vaporizes less than 5% of the liquid in the tubes resulting in a vapor/liquid mixture in the exhaust which is lower in density than is the supply LN_2. This density difference results in a net driving pressure that circulates enough liquid through the shroud to remove the heat load and keep the liquid at LN_2 temperature. Figure #8 shows the various stages and flow patterns in a typical tube and how they change as a function of heat load. The new SS/Loral shroud will function in the "saturated nucleate boiling" region. The fluid flow rate is calculated to be twenty to fifty times greater than the heat load will vaporize. Figure #9 shows the system with a modulating valve in the LN_2 supply line to each zone. This valve controls the liquid/vapor ratio (density) of the liquid in the tube and therefore determines its supply pressure.

THERMAL TESTING

Over the years, many aerospace companies have developed a standard procedure for performing thermal testing in vacuum chambers. Typically, an LN_2 shroud is used to simulate the cold black body of outer space, and a heating system, consisting of either cal rods or quartz lamps, is provided to simulate the sun's energy and counteract the cooling effects of the cryogenic shroud. Figure #10 shows a typical cal rod heater cage surrounding a part of a satellite. This technique has worked successfully, but has proven to be very costly in LN_2 consumption and in the associated efforts to build heater arrays, data systems and support structures. In the process of T/V testing, it has been discovered that a typical spacecraft operates during most of its orbital life not far from ambient temperature. Consequently, the required thermal conditions can be attained by designing the shroud to operate at whatever temperature is appropriate for the orbital conditions under test. For example, if a surface of a spacecraft experiences a temperature of, say +30°C, then it is obvious that this temperature could be achieved by setting the segment of the shroud facing that surface at +30°C, or at whatever temperature will cause the surface to reach that level. In other words, little is gained by averaging two extreme temperatures of an LN_2 shroud and heater system bucking each other to reach the desired surface temperature somewhere in between (in this example, +30°C).

Millions of dollars in recurring and non-recurring testing costs can be saved by utilizing a segmented thermal shroud whose temperatures can be accurately controlled within the spacecraft's operating temperature range. To accomplish this, each of the six segments of the new shroud can be set at any temperature between +150°C and -180°C. The new thermal shroud will be segmented into six independently controllable zones, one to match each surface of the spacecraft, and each zone temperature will be programmed to simulate the conditions it will experience in orbit. Mylar covered reflectors will be used to thermally isolate each surface from the other. It is calculated that the probable LN_2 consumption rate using this technique will be less than ten percent of that which the SS/Loral 39' chamber is now experiencing. Significant non-recurring cost savings will also be realized because it will no longer be necessary to design and build large heater cages, heater power systems, special cryopanels, a fixture to support all of this and the hundreds of thermocouples to monitor the temperatures on all of this hardware. These non-recurring costs on a typical satellite program at SS/Loral have exceeded $2 million.

The refurbished SS/Loral chamber will have a dual capability. First of all, it will have the ability using LN_2 to simulate the thermal extremes found in orbital space as is presently available, and it will also be able to provide the required thermal conditions by using a temperature controlled segmented shroud, whichever a customer or contract requires. Under either condition, the cost of thermal vacuum testing will be significantly lower than SS/Loral, and many other companies in the industry, are now experiencing.

DENSE GAS NITROGEN SYSTEM

Since a reliable GN_2 temperature control system is a relatively new technology in the thermal vacuum industry, and since it provides one part of the operation of the refurbished shroud, it is appropriate to describe its characteristics and capabilities.

Based upon their experience in the design and manufacture of first generation dense gas nitrogen systems, PSI has developed a new state-of-the-art second generation series called model TCU-1000 (figures #11, 12 and #13). This system includes a variable high speed centrifugal blower, a direct immersion electric heater and a compact spiral tube heat exchanger along with appropriate valves and sensors.

The control system provides precise temperature, dense GN_2 over a range of +150°C to -180°C within +/- 1° C. This control is achieved by maintaining a gas density of 0.4 lbs/ft^3 and gas flow at rates up to 650 CFM. During the cooling cycle, GN_2 flow is modulated through the heat exchanger to minimize LN_2 consumption and avoid using electric heat which is not needed. During the heating cycle, the appropriate power is provided by an SCR control. Although the method of control is sophisticated, operation is simple and precise. The only program required is the blower operating speed, temperature set point and ramp/soak cycle. All eight units are skid mounted, (caster mounting is available) with fully enclosed cabinets, and are completely insulated and purged to eliminate frost build up or condensation. The process piping is stainless steel and the units are available in 100, 300 and 650 CFM sizes.

WORK TO BE ACCOMPLISHED

Initially, all of SS/Loral's existing cryogenic equipment and systems will be removed. Those items include:

-LN_2 pumping skid and subcooler
-Model 1200 helium refrigerator skid
-Helium compressor skid
-GN_2 warm up skid
-48" Gate valve
-Entire LN_2 shroud
-All LN_2 piping
-Vacuum and cryogenic operating console

After this equipment has been removed, and when the time is appropriate, the following will be installed and interconnected:

- Gravity fed shroud including valves, lines and separator tank
- Twelve auxiliary zones, including valves and LN_2 transfer pumps
- 48" High vacuum gate valve
- Ambient starting roots blower
- Eight temperature control and distribution skids with piping and valves
- New vacuum and cryogenic control console

CONTRACTOR SELECTION

The refurbishment project contract was not circulated for competitive bidding. When SS/Loral established its design, the vendor was selected who was considered to be the most appropriate to provide the equipment required. In addition, the schedule that would have been lost by writing a definitive specification, followed by a bid span of at least eight weeks ending in whatever time would be required to read and evaluate all of the proposals was not acceptable. Instead, PSI Incorporated was identified as the company with the appropriate equipment, engineering skills and management experience that were needed to accomplish the project within the technical, financial and schedule restraints previously noted. Initially, a study contract was awarded to PSI to design the systems, identify the costs and determine the schedule for the refurbishment work to follow. During this study, SS/Loral and PSI engineers worked together identifying requirements and sharing design ideas. This creative and interactive process produced a design that satisfied SS/Loral's requirements and gave PSI a clear understanding of what was required and how the new system will be used. This partner relationship between the two companies is somewhat unique in the industry, but has resulted in a greater understanding by both companies of all aspects of the job. In recent years, Dr. W. Edwards Deming has taught American industry that competitive bidding in a highly technical project is not necessarily as effective as the creation of a partner relationship between the user and supplier from which both parties benefit. This contract has so far confirmed the validity of that concept.

CONCLUSION

There are many large thermal vacuum chambers throughout the aerospace industry that have been in operation for more than twenty five years. During that time, they have been used successfully to test spacecraft in various space and defense programs. Although some of the country's weapons systems programs have recently been reduced or eliminated, there appears to be future business in the communication and weather satellite area. It seems to be an important requirement that aerospace companies who intend to be competative have modern and efficient thermal vacuum test facilities. Of the aerospace firms that have their own, somewhat aging, thermal vacuum test chambers, the question arises of how to bring them up to modern standards. The stainless steel shells of these chambers are not likely to deteriorate. The aluminum shrouds and their associated cryogenic systems, however, are a different matter. The replacement of aging and failing shrouds seems to be an appropriate opportunity to take advantage of the new cryogenic systems now available. To increase operating efficiency, recent improvements in cryogenic equipment and GN_2 systems are now available that offer a low cost alternative to traditional thermal vacuum testing. To upgrade these facilities then, a refurbishment of the typical shroud and LN_2 system is a cost effective way to reach this goal and provide a state of the art facility without completely replacing or duplicating existing chambers.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

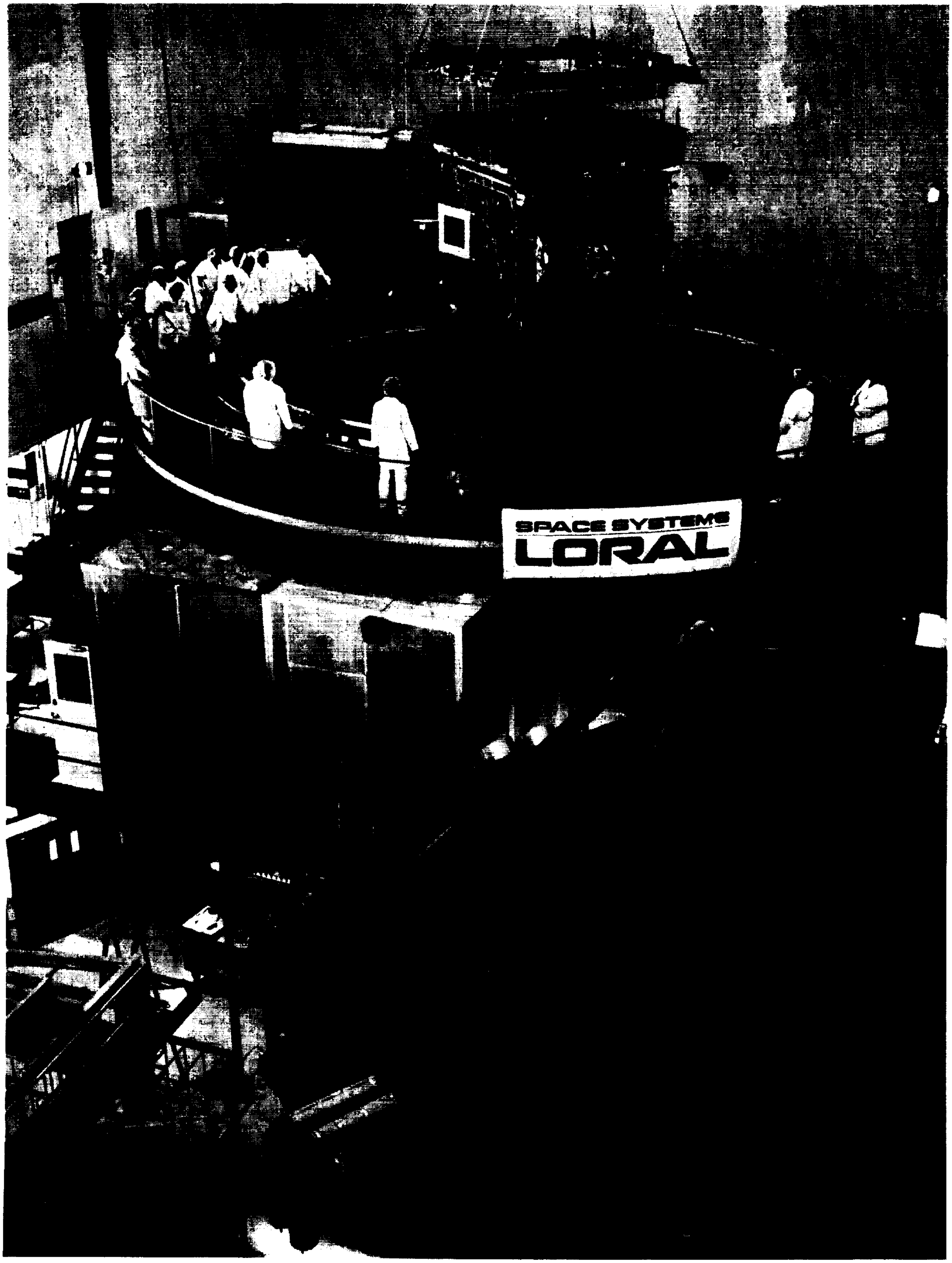


FIGURE 1

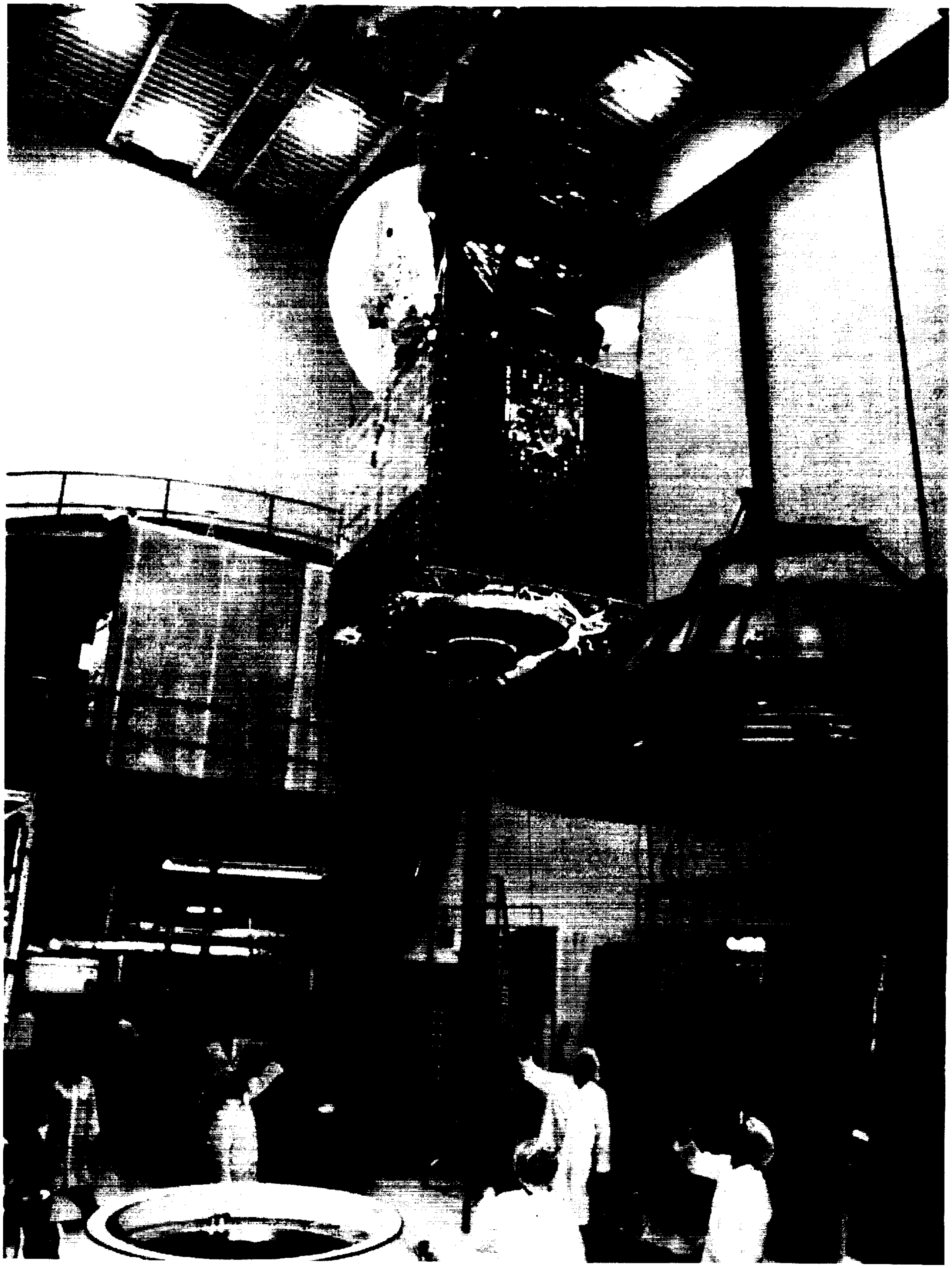


FIGURE 2

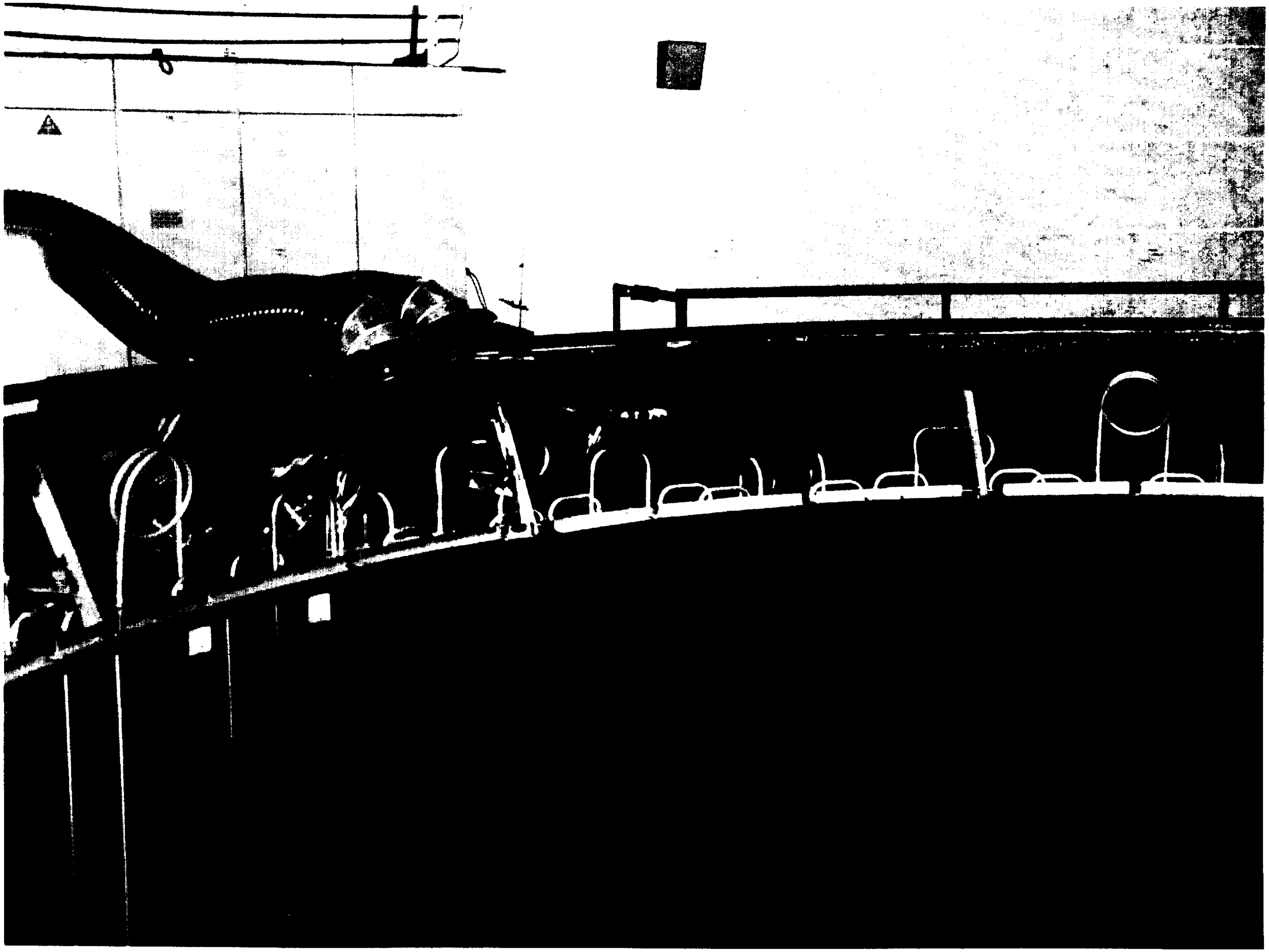


FIGURE 3

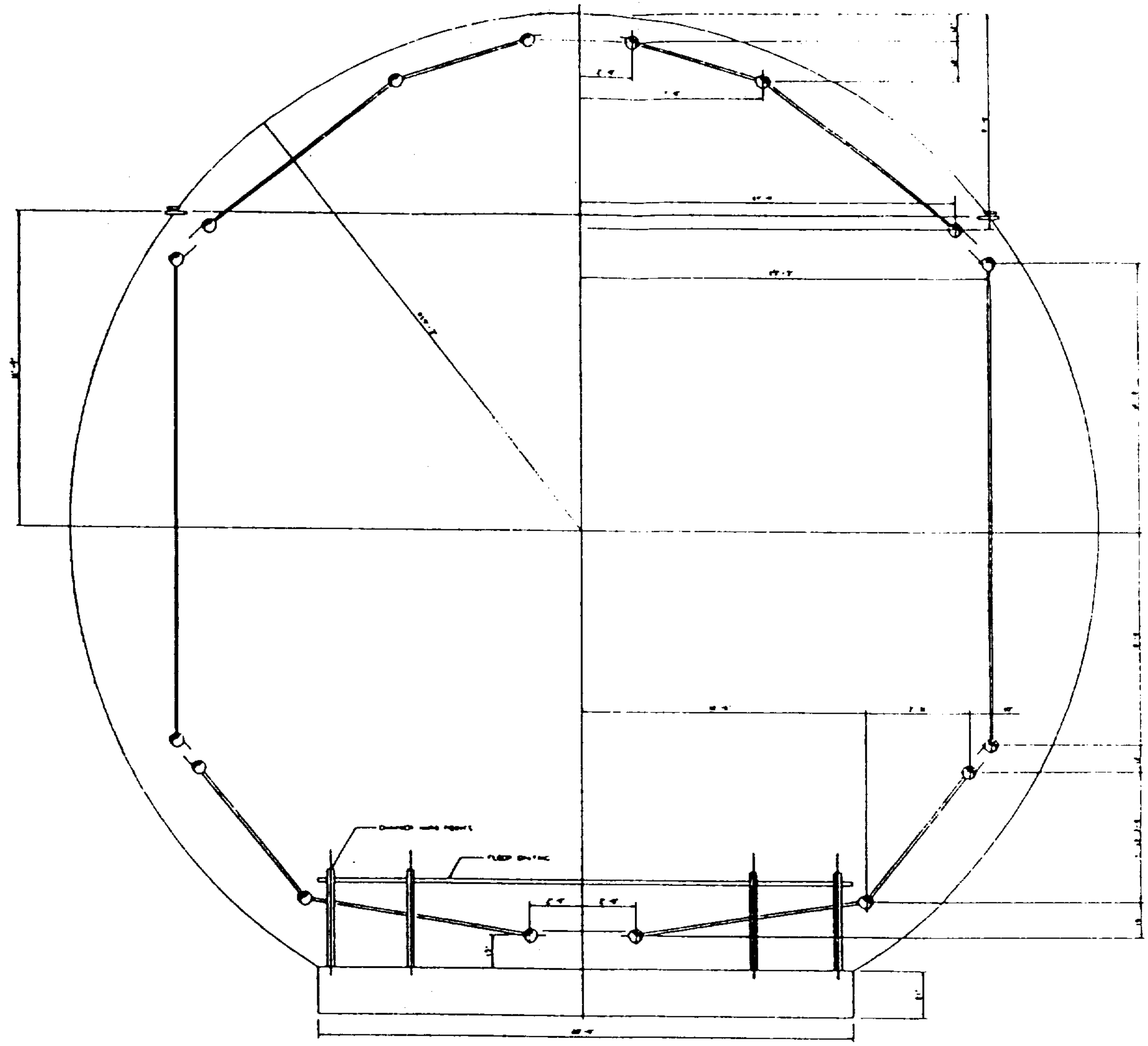


Figure 4

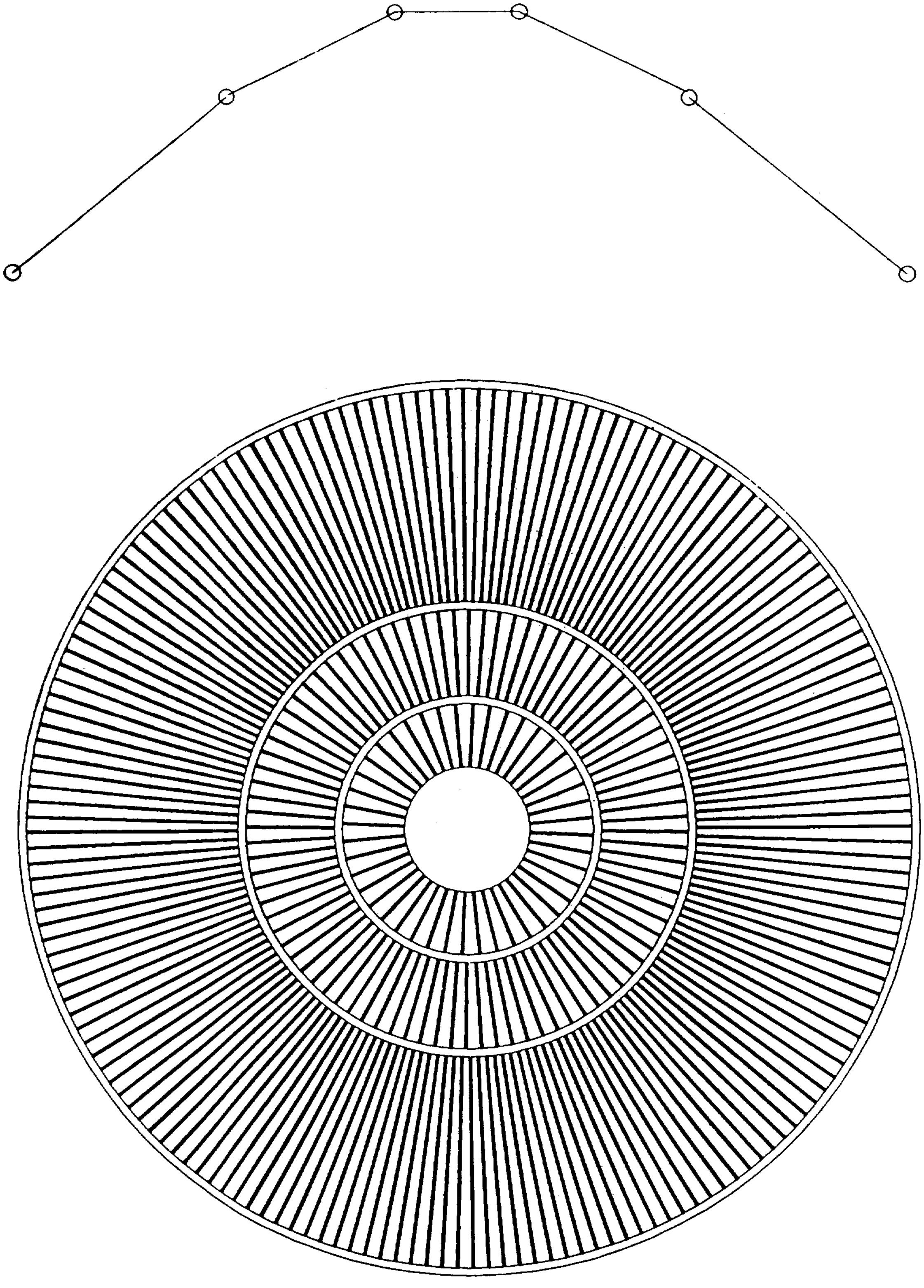


Figure 5

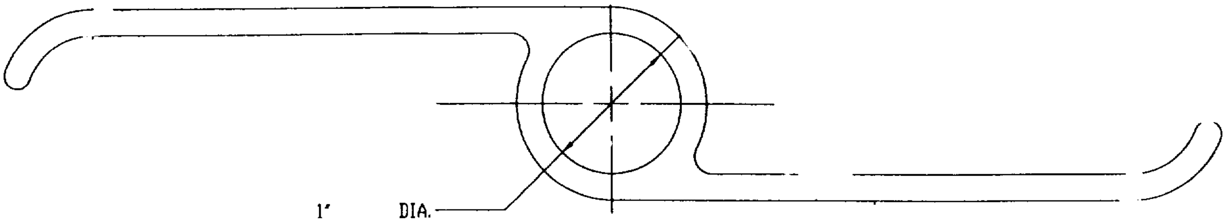


Figure 6

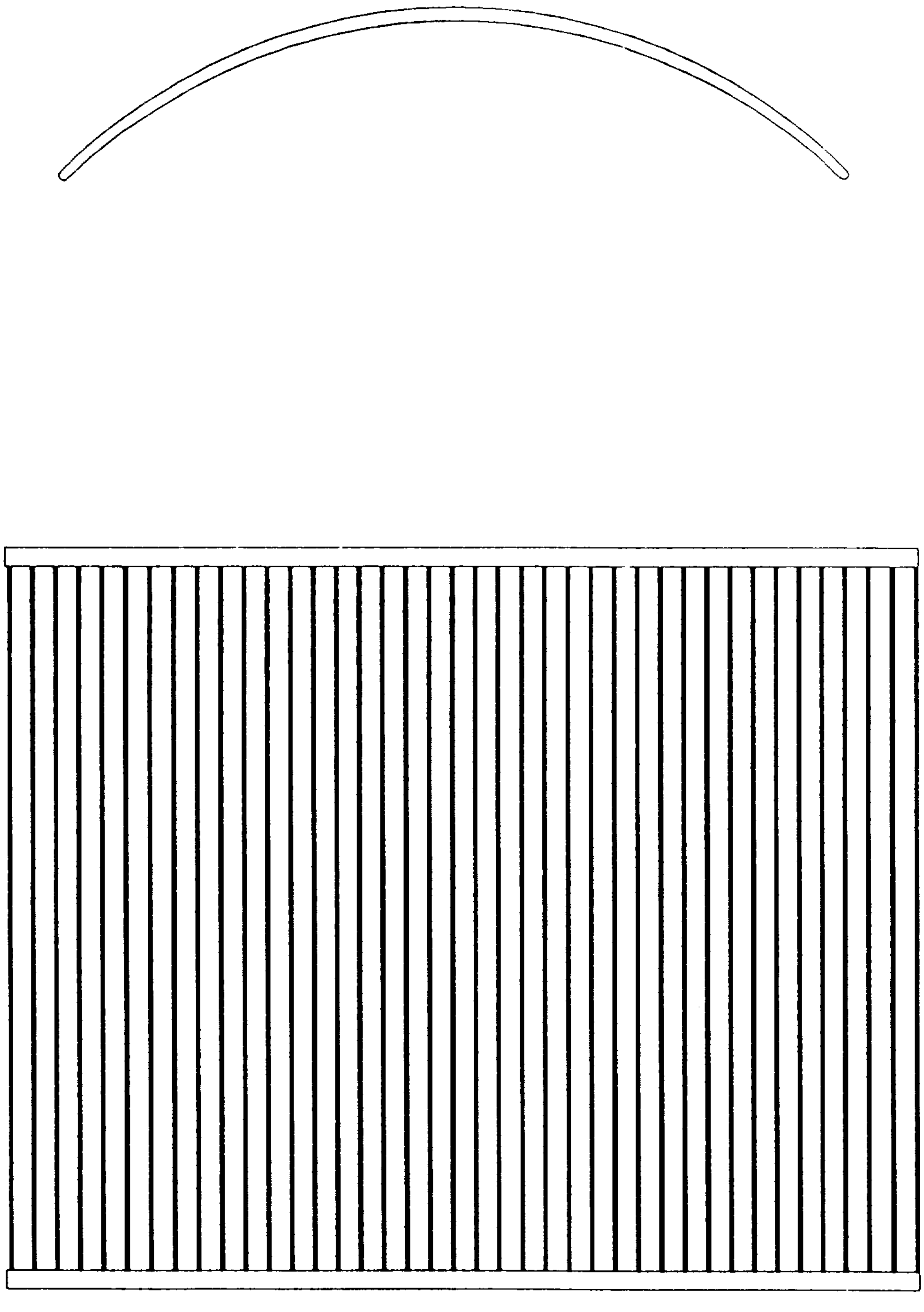


Figure 7

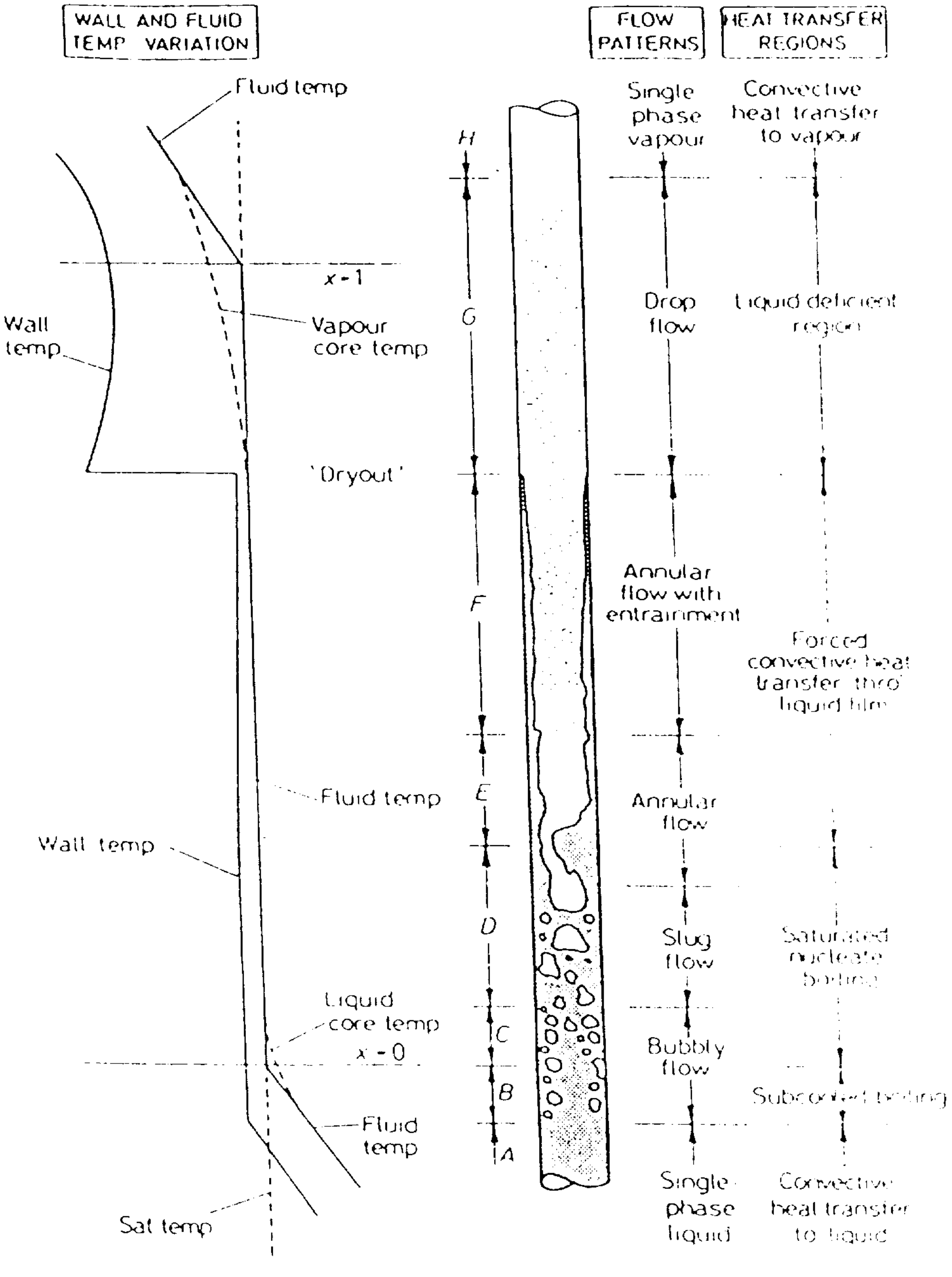

WALL AND FLUID TEMP VARIATION
FLOW PATTERNS
HEAT TRANSFER REGIONS
Fluid temp
$x = 1$
Wall temp
Vapour core temp
'Dryout'
Fluid temp
Wall temp
Liquid core temp
$x = 0$
Fluid temp
Sat temp
H
G
F
E
D
C
B
A
Single phase vapour
Drop flow
Annular flow with entrainment
Annular flow
Slug flow
Bubbly flow
Single phase liquid
Convective heat transfer to vapour
Liquid deficient region
Forced convective heat transfer thro' liquid film
Saturated nucleate boiling
Subcooled boiling
Convective heat transfer to liquid

Figure 8

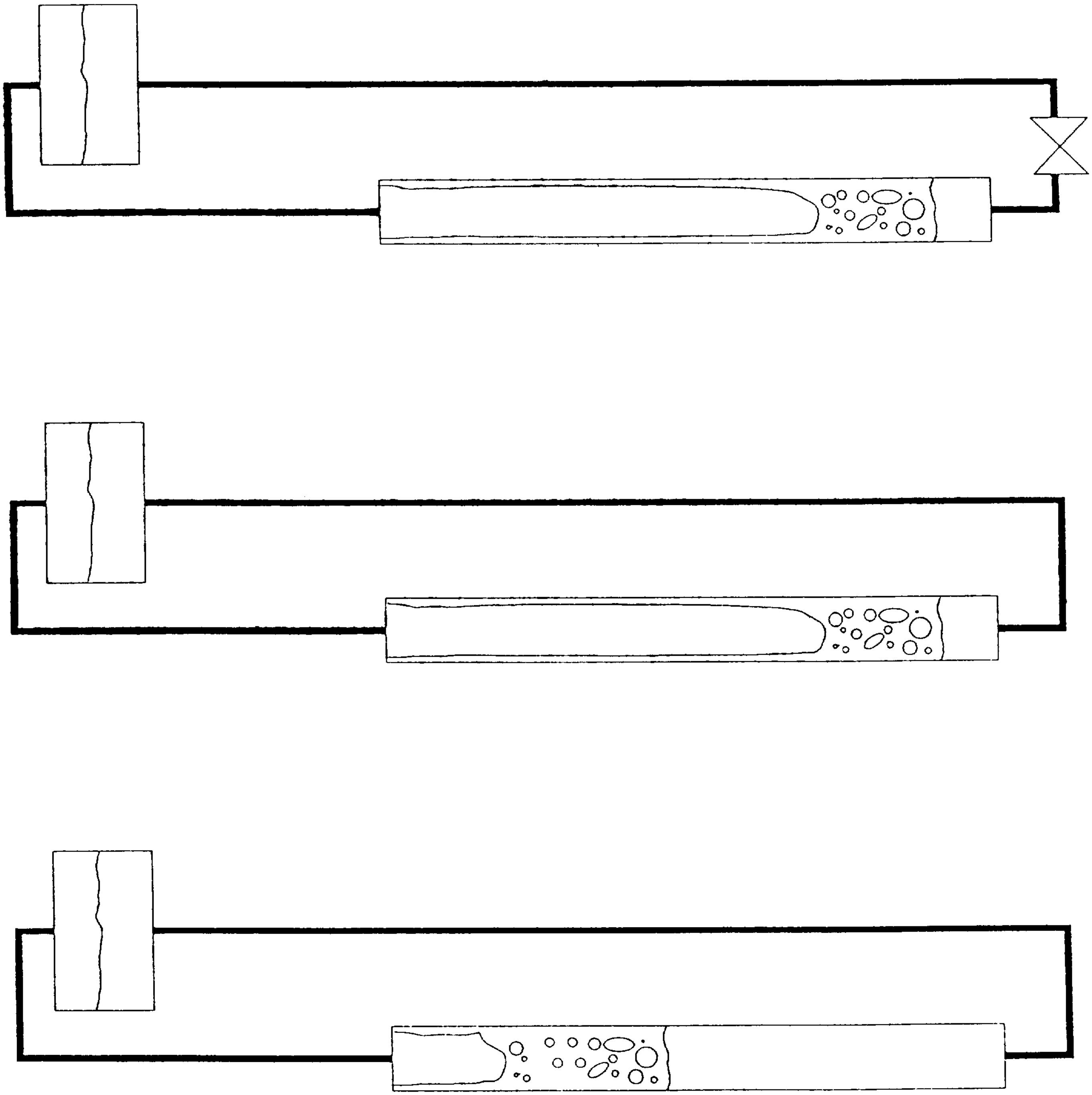


Figure 9

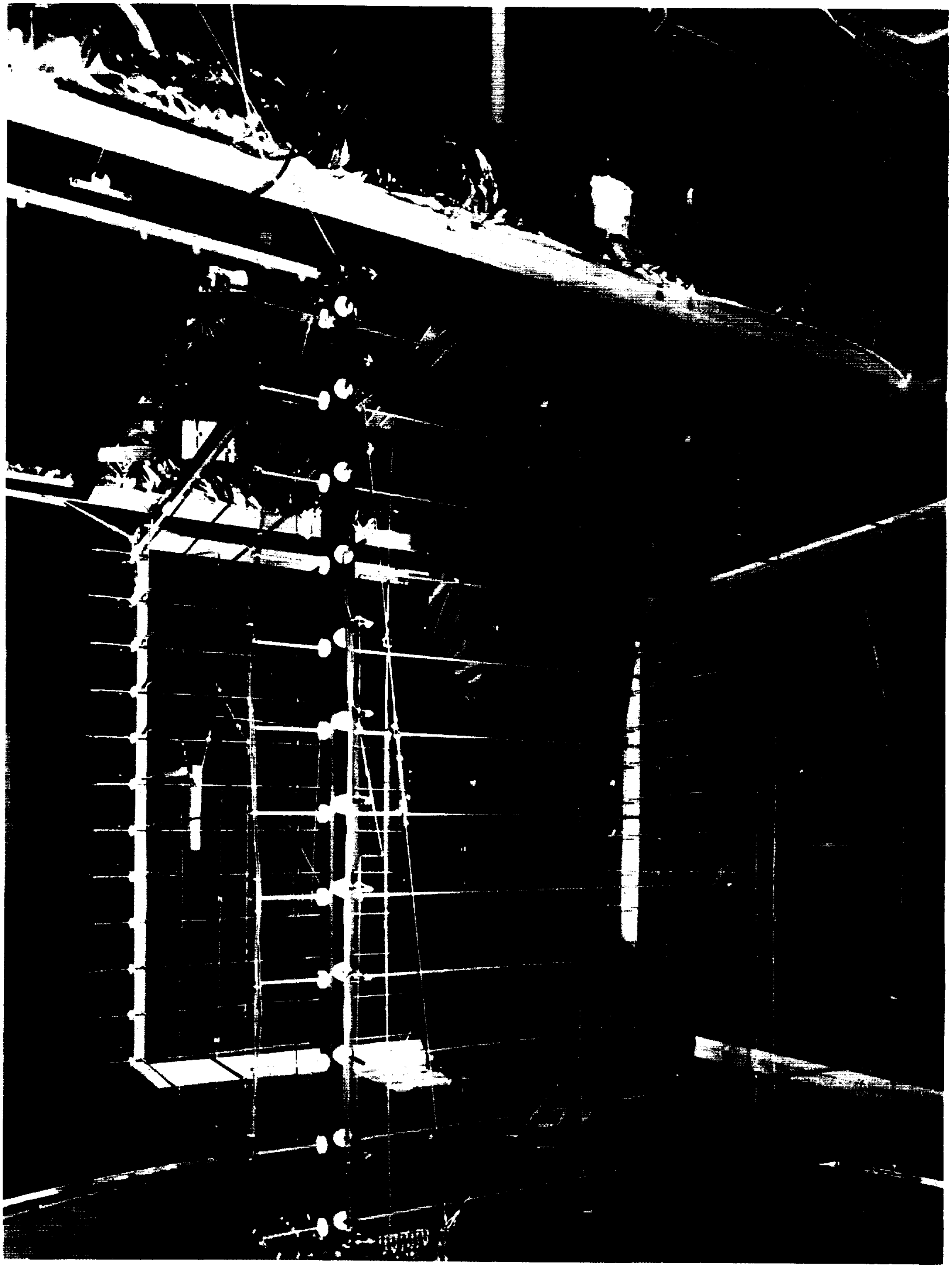


FIGURE 10

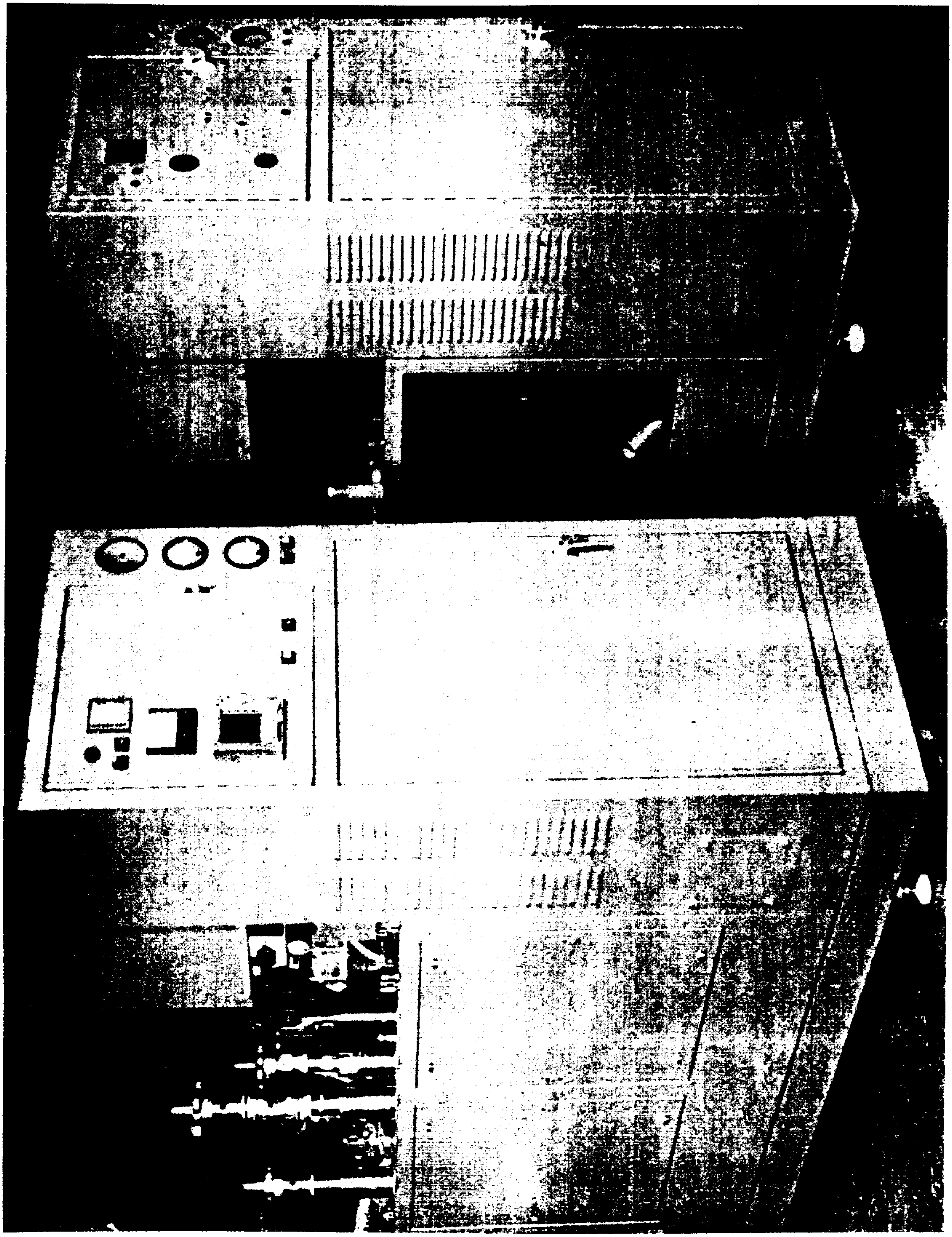


Figure 11

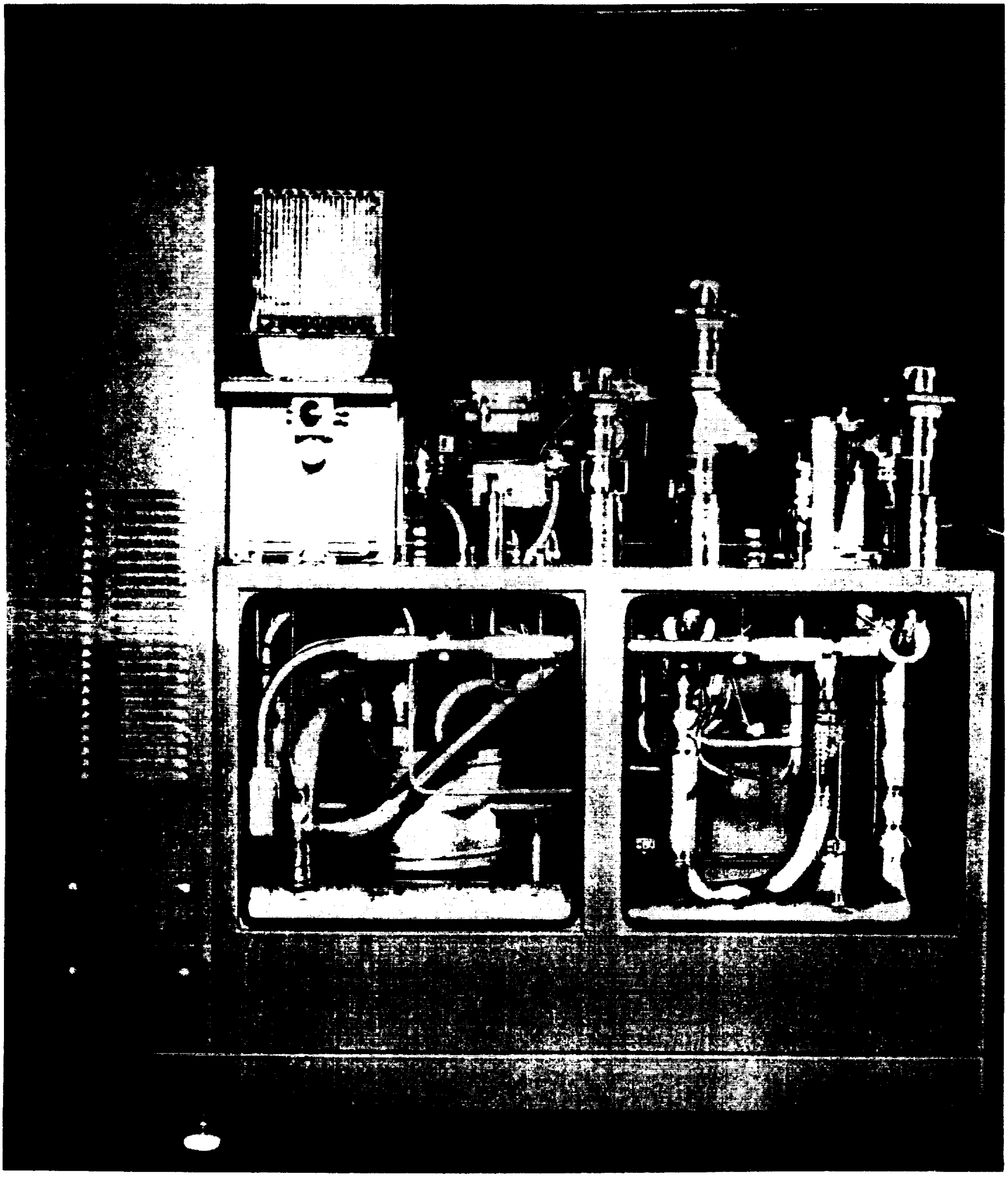


Figure 12

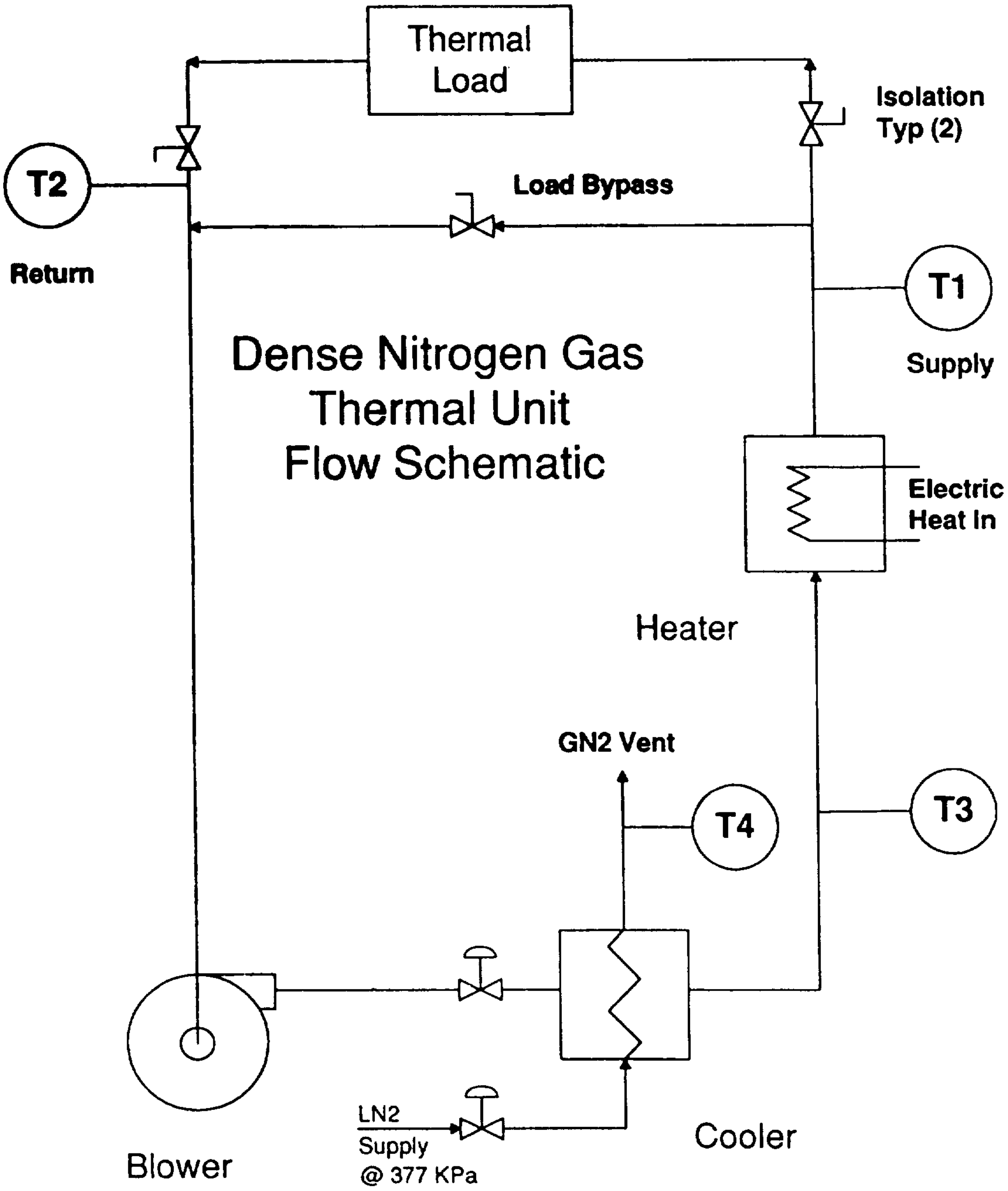

Thermal Load
Isolation Typ (2)
T2
Load Bypass
Return
T1
Dense Nitrogen Gas Thermal Unit Flow Schematic
Supply
Electric Heat In
Heater
GN2 Vent
T4
T3
LN2 Supply @ 377 KPa
Cooler
Blower

Figure 13

Typical Cracked LN_2 Tube
Figure 14

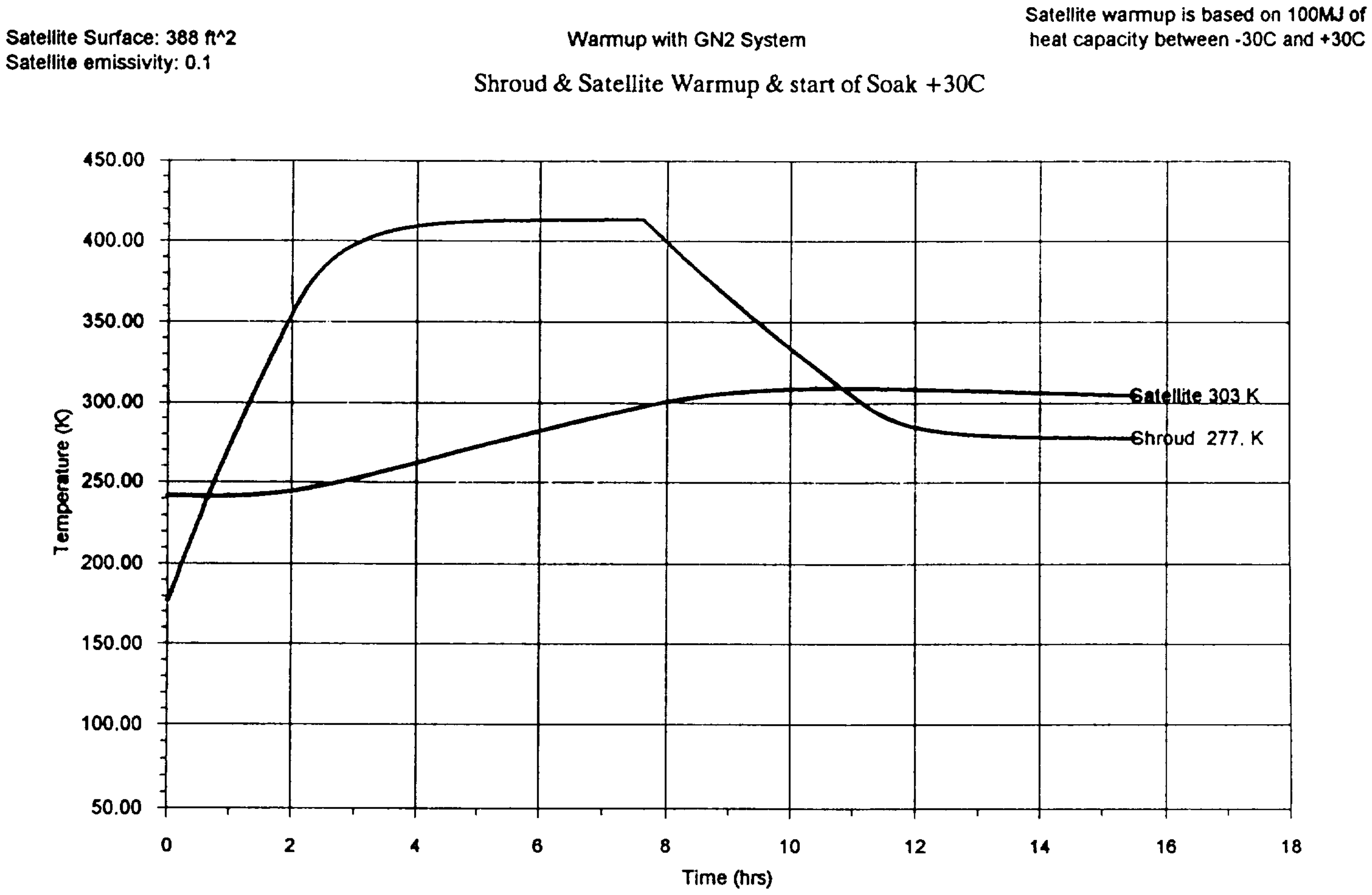

Satellite Surface: 388 ft^2
Satellite emissivity: 0.1
Warmup with GN2 System
Satellite warmup is based on 100MJ of heat capacity between -30C and +30C
Shroud & Satellite Warmup & start of Soak +30C
450.00
400.00
350.00
300.00
250.00
200.00
150.00
100.00
50.00
Temperature (K)
0
2
4
6
8
10
12
14
16
18
Time (hrs)
Satellite 303 K
Shroud 277. K

Figure 15

Temperature difference (supply - return) = 60K

SPACE SYSTEM / LORAL

Shroud Mass 9500 kg
Transfer Lines Mass 2200 kg
Shroud Enthalpy @ 85K 1.28E+8 Joules
@425K: 2.71E+9 Joules

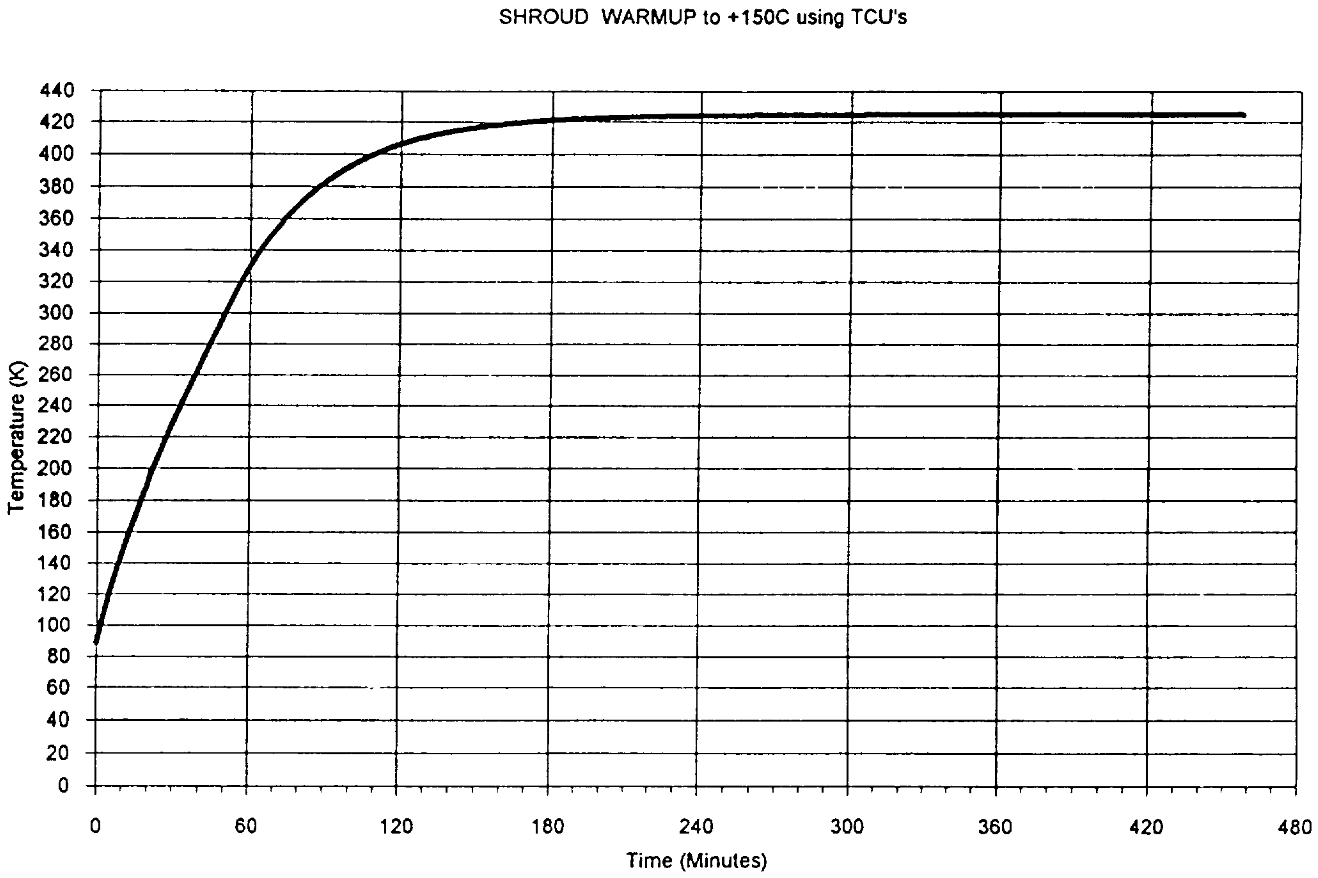
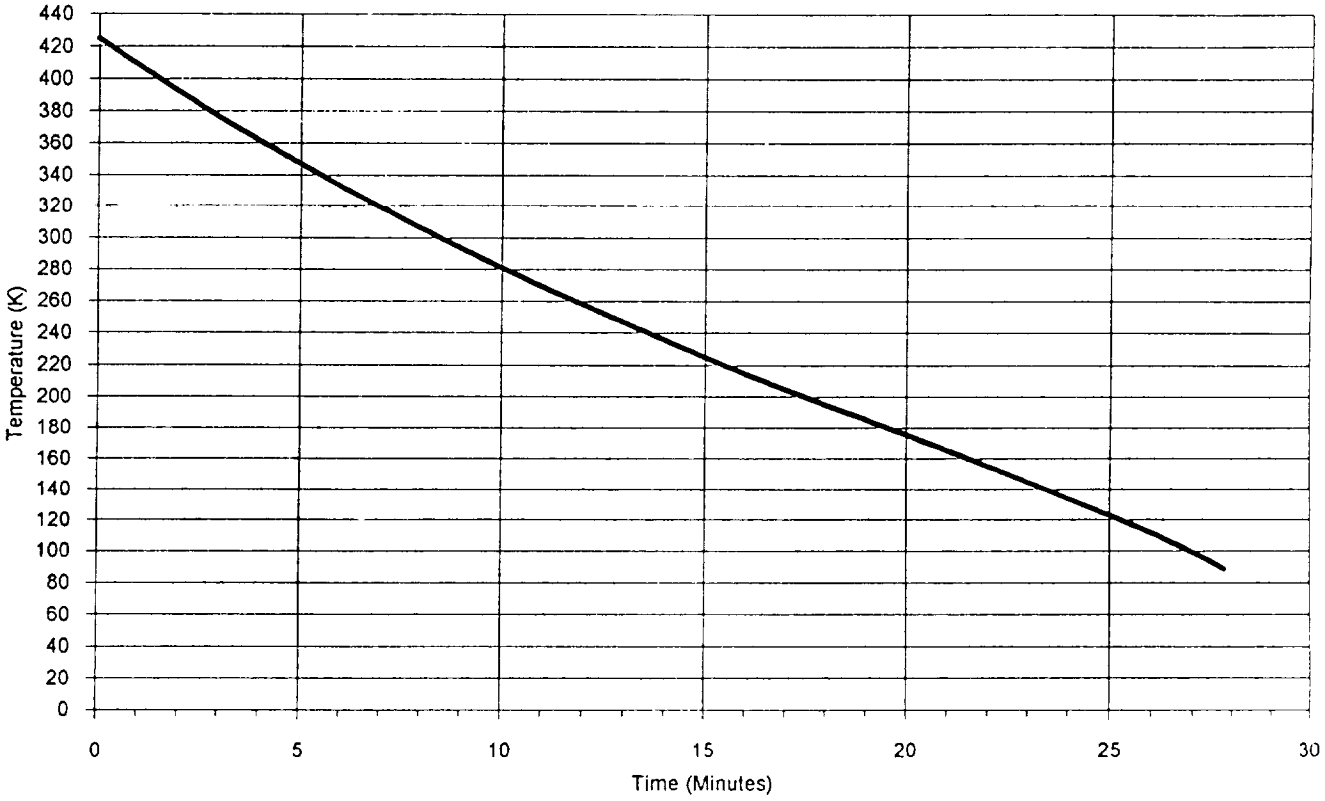


Figure 16



Supply Flowrate: 5.9 kg/s

SPACE SYSTEM / LORAL

Shroud Mass 9500 kg
Shroud Enthalpy @425K: 2.71E+9 Joules
@85K: 1.28E+8Joules

SHROUD COOLDOWN with LIQUID NITROGEN

Figure 17