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Conceptual Design of Liquid Droplet Radiator Shuttle-Attached Experiment

Technical Requirements Document

Shlomo L. Pfeiffer
Grumman Space Systems
Bethpage, New York

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Abstract

The technical requirements of a shuttle-attached Liquid Droplet Radiator (LDR) experiment are discussed. The Liquid Droplet Radiator is an advanced lightweight heat rejection concept that can be used to reject heat from future high powered space platforms. In the LDR concept, submillimeter sized droplets are generated, pass through space, radiate heat before they are collected and recirculated back to the heat source. The LDR experiment is designed to to be attached to the shuttle longeron and integrated into the shuttle bay using standard shuttle/experiment interfaces. Overall power, weight, and data requirements of the experiment are detailed. Shuttle integration and safety design issues are discussed. An overview of the conceptual design of the experiment is presented. Details of the conceptual design are not discussed here , but rather in a separate Final Report.

1.0 Introduction

Future space applications will require the development of advanced light weight heat rejection systems. The liquid droplet radiator is a heat rejection system which holds much promise for fulfilling the need for lightweight heat rejection. To establish feasibility in a relevant environment, the liquid droplet radiator is proposed for a space flight test aboard the space shuttle. This document will detail the development of the droplet radiator, discuss technical issues which the proposed experiment will address, and detail how the experiment will be integrated into the shuttle bay.

2.0 Background

Future space platforms will grow in size and will have an increasing need for lightweight, efficient waste heat removal systems. The heat rejection system can be the dominant weight in space platforms which require more than a few hundred kilowatts of heat rejection. The liquid droplet radiator (LDR) is an advanced heat rejection concept that promises to reject large amounts of waste heat in a low weight and cost effective manner.

A conceptual design of the LDR system is illustrated in Fig. 1. The waste heat fluid is pumped from the space platform to the LDR where it is generated into submillimeter droplets. The droplets radiatively cool as they pass through space from the droplet generators to the collectors. The fluid is then recirculated back to the heat source.

The LDR concept was conceived in 1978. Several different LDR configurations were proposed including spiral, enclosed disc, annular and magnetic. These concepts are illustrated in Fig. 2. Currently the two LDR configurations which are considered the most viable, and which are the most extensively studied, are the rectangular and triangular LDR (Fig. 3). NASA Lewis and the Air Force Astronautics Lab have been involved in funding and investigating many aspects of the development of these concepts.

Studies of the rectangular and triangular LDR concepts have been investigated by Grumman (Ref. 1), University of Washington (Ref. 2) and McDonnell Douglas (Ref. 3). Hardware fabrication and testing of the LDR generator and collector have been performed by several organizations including: NASA Lewis, University of Southern California, University of Washington, Grumman and McDonnell Douglas. Reference 4 gives a detailed background of the LDR issues, concepts and developments that have been pursued to date.

Grumman has been involved in LDR development since 1984. Under contract to the Air Force, Grumman built and tested a linear droplet collector with an integrated positive displacement pump (Ref. 5). The contract included a research-type effort on film flow and droplet impingement with passive collectors. A passive collector with an integral gear pump was built and tested; Fig. 4 is a photograph of a droplet streams impinging on a linear droplet collector pump. The collector was able to capture, in vacuum, DC-704 liquid droplet streams generated from a 900-hole, 100 μm orifice plate. The generator was built by Grumman and the orifice plate was supplied by NASA Lewis. Grumman has also published results of analytical work characterizing LDR heat transfer considerations and droplet fluid dynamic behavior (Ref.1,7).

2.1 Objectives of the Experiment

This LDR Outreach Study develops a conceptual design of a shuttle attached experiment that will demonstrate an integrated LDR system working in a space environment. Fig. 5 shows a pictorial of the shuttle attached experiment. All the major components that would be required for a future "full-up" LDR system are included and these components have operating characteristics similar to those expected of future systems.

Many of the LDR related technical issues have been studied analytically and some of the critical components, such as the generator and collector, have been built and tested. The objective of the shuttle attached experiment is to investigate physical phenomena that cannot be adequately tested in a one-g or transient zero-g environment and to demonstrate the operation of an integrated LDR system.

The fluid dynamics of the LDR linear collector have been studied analytically but many technical issues cannot be properly characterized in a one-g or transient zero-g environment. As described in Section 4.0, the forces which drive the fluid into the collector throat are quite small - typically the pressures that are generated will be 1 to 3 psia. At these pressure levels it is not possible to discern the gravity effects from the other fluid forces. Reference 7 investigates droplet collection using passive collection techniques. Formulae are developed which describe fluid velocities and liquid layer thicknesses at various locations in the collector throat. These formulae are valid only for droplets that are part of the mainstream of the fluid; that is, at the center of the collector mouth where steady streams of droplets impinge on the back surface of the fluid. The conditions that exist at the fringes of the collector surfaces cannot be accurately characterized without a long-term in-flight zero-g experiment. Although recent analysis indicates that there will be no backflow of fluid from the collector mouth, because of the small forces involved, this measurement can, also, only be tested in a true long-term zero-g space environment. Another important issue that will be demonstrated in the space flight test is the operation of the shear seal valve at the generator. The shear valve mechanism is detailed in Fig. 6. The purpose of the valve is to minimize the amount of fluid loss during startup and shutdown of the LDR generator and to eliminate the buildup of fluid on the orifice plate. Drop tower tests at NASA Lewis have shown that a buildup of fluid on the exterior of the orifice plate will cause misdirection of the droplet stream at generator startup. Below are listed the major issues which will be studied in the experiment. Those marked with an asterisk are issues that cannot be tested in a one-g environment or in the transient zero-g environment of a KC-135 flight or a drop tower test:

- Startup
  - *– Generator start/stop performance
  - *– Generator surface wetting and droplet misalignment
  - – Establishing stable film flow on collector surfaces
- Steady run
  - – Droplet stream characteristics
  - – Droplet loss rate
  - *– Collector operation
  - – Boost pump operation
  - – Droplet heat transfer characteristics
  - *– Fluid backflow from collector surface
- Shutdown
  - *– Effect of fluid decay on collector operation
  - *– Generator shear seal operation

In addition to the aforementioned issues, one of the objects of the experiment will be the demonstration of the manufacturability of an orifice plate with several thousand holes that can achieve less than 5 mrad parallelism. Besides the specific technical information that will be gained from the LDR experiment, there will be the added benefit of allaying the fears of future LDR users regarding droplet loss, spacecraft contamination, etc. Traditionally, an advanced concept will not be considered for a future space application unless it has been demonstrated in space.

2.2 Potential Missions

Future NASA and Air Force heat rejection requirements will far exceed the heat rejection levels of current satellite systems. Table 1 lists possible future LDR applications and predicts their heat rejection requirements. Current state-of-the-art heat rejection systems such as heat pipe radiators weigh about 13 to 18 kg/kW (at ~300 K) - excluding the weight of the interface mechanism. A high power space station may have a heat rejection requirement as high as 200 kW which translates into a 3500 kg (7700 lb) system weight for the radiators alone. Conversely for the same heat rejection load, an LDR system would weigh about 500 kg (1100 lb) - including the weight of the generators, collectors, piping and supporting structure.

Reference 6 reviews the suitability of many advanced heat rejection concepts to specific system requirements. The requirements included heat rejection load, weight, size, volume, launch loads and maneuverability. The results of the study indicate clearly that for fluid temperatures below approximately 700 K, the LDR system is significantly lighter in weight than the other advanced radiator concepts. Fig. 7 shows the LDR system weight in comparison to the heat pipe, Curie point, moving belt and rotating bubble membrane radiator system weights. Fig. 8 illustrates the relative weights of the various subsystems to the total heat rejection system weight for each concept.

3.0 Payload Accommodation

One of the key goals in the design of the LDR experiment is to make its integration into the shuttle bay as simple and as straightforward as possible. To do this, all of the aspects of the integration - structural, dynamic, data handling, control and power - are all kept within the constraints of standard shuttle experiments.

As mentioned in Section 2.1, the LDR shuttle attached experiment has several goals. The primary purpose is to investigate the fluid dynamic interactions that are not possible to monitor in a one-g or in a transient zero-g environment (i.e., drop tower tests or KC-135 flight tests). Another important aspect of the experiment is to demonstrate to the user community that the LDR system is a viable heat rejection concept and that it will not contaminate the space platform. A major concern of the user community is that stray droplets will degrade the performance of a spacecraft by impinging on its optical or thermal control surfaces. In order to design an experiment that will demonstrate an extremely low droplet loss rate (i.e., $1:10^8$), it is necessary that the generator-to-collector path length be long and that there be a diagnostic system which will detect any LDR droplets that stray outside the permissible envelope. The Grumman shuttle attached SHARE (Space Station Heat Pipe Advanced Radiator Element) experiment which flew in March 1989 aboard Discovery and the Grumman SRAD (Space Radiator Assembly Demonstration) experiment both have similar payload dimensional requirements - namely a long aspect ratio. The location of the experiments in the shuttle bay is in the 38.1 cm (15 in) diameter envelope opposite the shuttles' remote manipulator arm, as shown in Fig. 9. To take full advantage of related experience and to minimize the integration effort, the LDR experiment was designed to fit within all the weight, power, data and control constraints imposed on the SHARE experiment.

The proposed LDR experiment will be mounted onto the SRAD beam. The SRAD beam has been designed to handle the shuttle induced loads through ascent and descent with 123 kg (270 lbs) of heat pipe radiators attached to it. The LDR experiment is estimated to weigh 73 kg (160 lbs). The flight path of the droplets will be 6.1 m (20 ft) and the entire experiment will fit within a 38.1 cm (15 in) diameter dynamic envelope. The 6.1 m (20 ft) generator-to-collector path length was chosen assuming that the angular divergence of the droplet streams will not exceed 5 mrad. Using this path length, the droplet streams come close to the walls of the enclosure which encapsulates the experiment. The overall length of the LDR experiment, including all auxiliary equipment, will be approximately 9.1 m (30 ft).

Fig. 10 details a cross-section of the LDR enclosure. The enclosure which encapsulates the experiment is a leak tight structure manufactured out of 0.102 cm (0.040 in) thick sheet aluminum with ribs every twelve inches. A major consideration in the design of the LDR enclosure is the pressure changes induced during shuttle ascent and descent. Fig. 11 details the pressure changes during shuttle launch (Ref. 8). The pressure change between the shuttle bay and the LDR enclosure is controlled with a series of check valves and solenoid latch valves. Specific design issues are discussed in Ref. 9.

As mentioned previously, the LDR experiment is designed to be integrated into the shuttle bay and to operate using standard shuttle experiment electrical power - 28 VDC and 1750 W continuous 3000 W peak power. It is estimated that the maximum power requirements for the LDR experiment will be less than 1200 W continuous power.

The effect of the shuttle accelerations on the droplet generator-to-collector path was investigated. Reference 8 details the maximum accelerations that can be expected from the shuttle's vernier RCS system. Preliminary results of the investigation show that under worst case conditions the droplets will only deviate from their paths by a maximum of 0.8 inches in any direction. Thus, the experiment can operate through all the vernier accelerations. The LDR will not be able to operate during main thruster acceleration; these accelerations normally take place once every 4.5 hours.

3.1 Crew Involvement

The LDR experiment will be controlled via an astronaut/ground station link. The astronaut will use the Standard Switch Panel (SSP) illustrated in Fig. 12 to control all the vital functions of the experiment. The astronaut will receive support and direction from the ground station and will monitor the experiment throughout its estimated three hour operation. The experiment can be automated so that little or no astronaut intervention is necessary, but that would significantly increase the complexity of the experiment.

4.0 Experiment Definition

A schematic of the LDR experiment is shown in Figure 13 and an isometric drawing of the experiment is detailed in Fig. 14. Reference 9 details all the components of the experiment and discusses their power, weight and instrumentation requirements. A brief description of the major components of the LDR experiment follows:

Generator:
The experiment will use Dow Corning 704 silicone oil, which is a well characterized, stable, low vapor pressure fluid and relatively low cost. The droplets are formed at the droplet generator. The primary function of the generator is to ensure the production of uniform drops at the desired operating conditions. This is accomplished through the use of a driven acoustic cavity which creates a pressure perturbation at the orifice array. Unlike conventional ink-jet printer array drop generators, the LDR experiment requires multiple droplet velocities and thus multiple frequency operation. This requirement necessitates a cavity and transducer capable of delivering the required pressure over the frequency range of interest.

Collector:
After the droplets are generated and pass through space, they are collected by the LDR collector. The collector is a wide throat positive displacement gear pump. Figs. 15 and 16 detail the design of the collector. The fluid from the droplet streams is collected in the throat of the collector and is forced into the gears by the pressure of the droplet streams on the back side of the fluid. The pump shown is representative of what a collector pump on a "full-up" system would look like. One of the key features of the linear collector pump is that the droplet streams from the different generator modules do not have to be focused on a single collector, as is the case for the centrifugal collector concept. The output pressure of the collector is kept low so that the gears, housings and motor will be kept as lightweight as possible. The collector weighs an estimated 0.71 kg/m (5.1 lb/ft). One of the major benefits of the linear collector design is its simplicity. Another aspect of the linear design which will be important from a

systems standpoint is its survivability. If one of the collector modules malfunctions or is destroyed by a meteorite, that particular module (and its associated generator) can be turned off without significantly affecting the heat rejection capacity of the whole system.

Droplet Loss Detection System:

The droplet loss detection system will count the number of stray droplets and calculate the droplet velocity and position. The droplets will be detected by reflections from a scanning laser beam which will oscillate around the perimeter of the droplet stream.

Transport:

After the fluid is discharged from the collector pump it goes into the high pressure boost pump which will boost the fluid up to the pressures required for proper droplet formation at the generator. The experiment will be run at droplet velocities of 2, 4, 6 and 10 m/sec with the 6 m/sec droplet velocity considered the design point. Data will be collected at these velocities in order to measure the effect of the different droplet velocities on collector/generator performance.

5.0 Conclusions

This Technical Requirements Document has outlined the technical requirements a shuttle-attached liquid droplet radiator experiment. Size, power, weight, data and instrumentation requirements of the experiment are detailed. A key factor in the design of the experiment is the integration of the experiment into the shuttle using standard shuttle/experiment interfaces. The experiment weighs approximately 73 kg (160 lbs), is less than 9.1 m (30 ft) long and fits within a 38.1 cm (15 in) diameter. Further details of the experiment are discussed in Reference 9.

6.0 References

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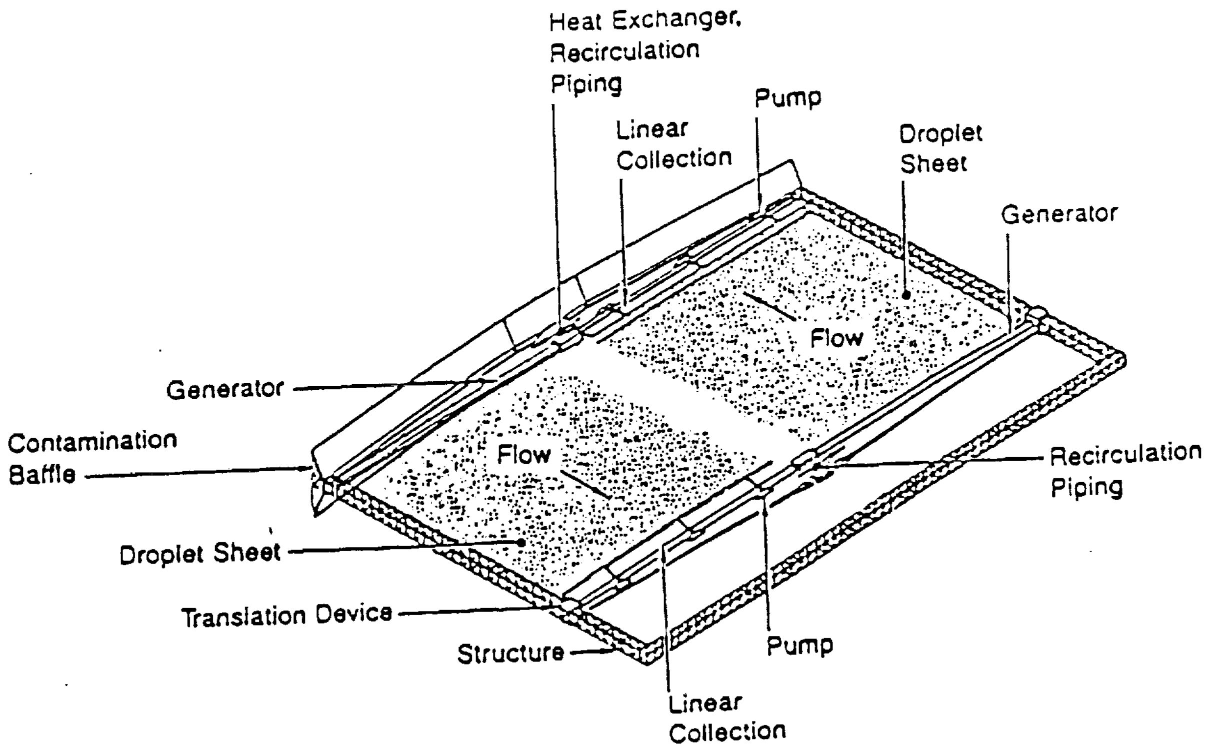


Figure 1 Conceptual Design of LDR System

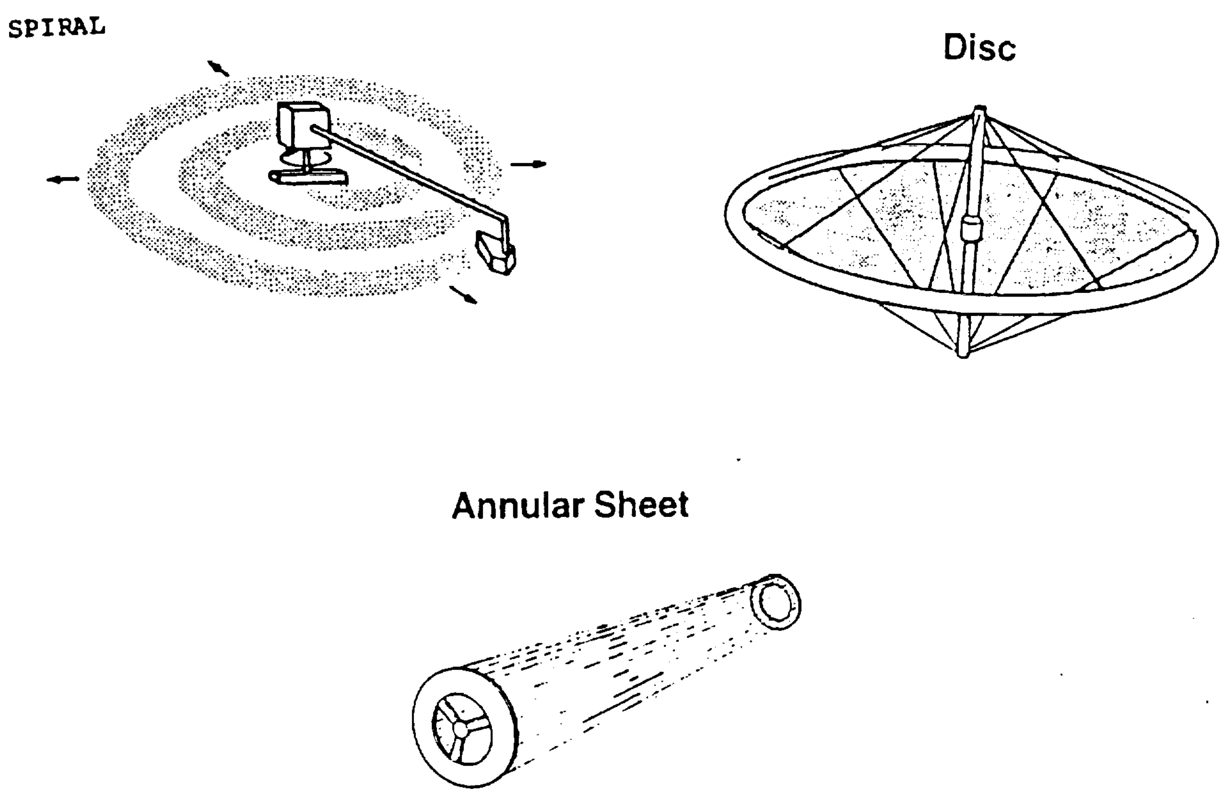
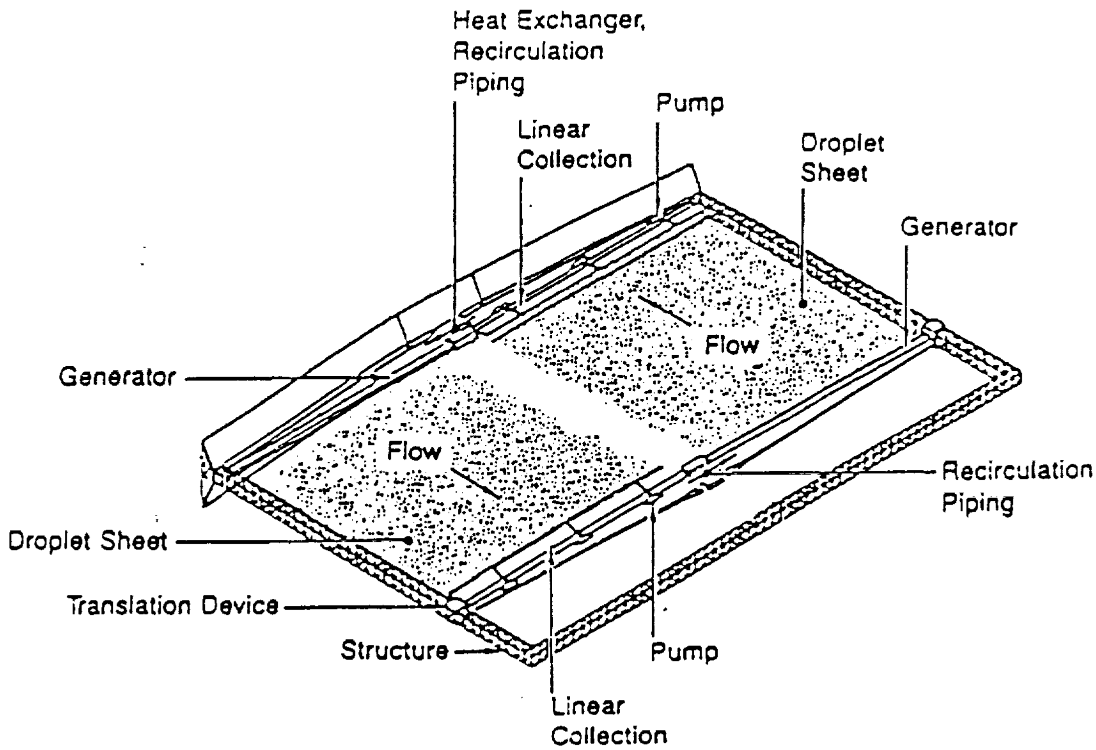


Figure 2 Various Proposed LDR Configurations



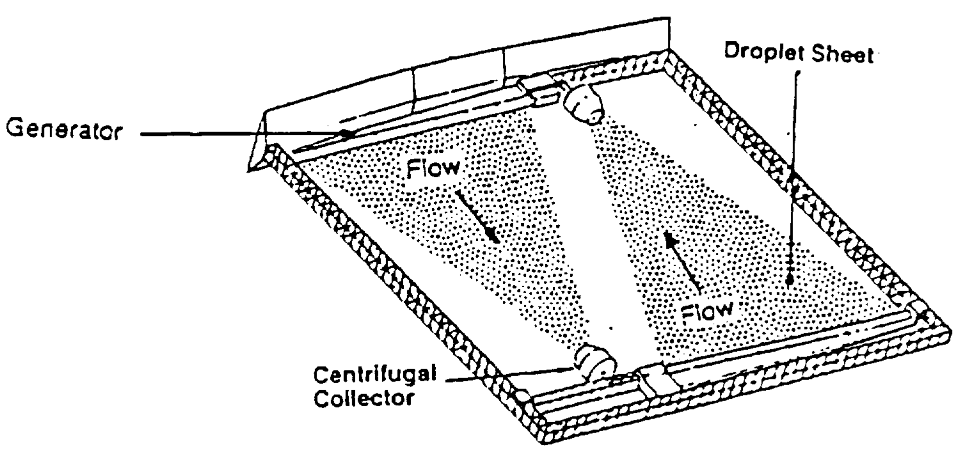


Figure 3 Rectangular & Triangular LDR Configurations

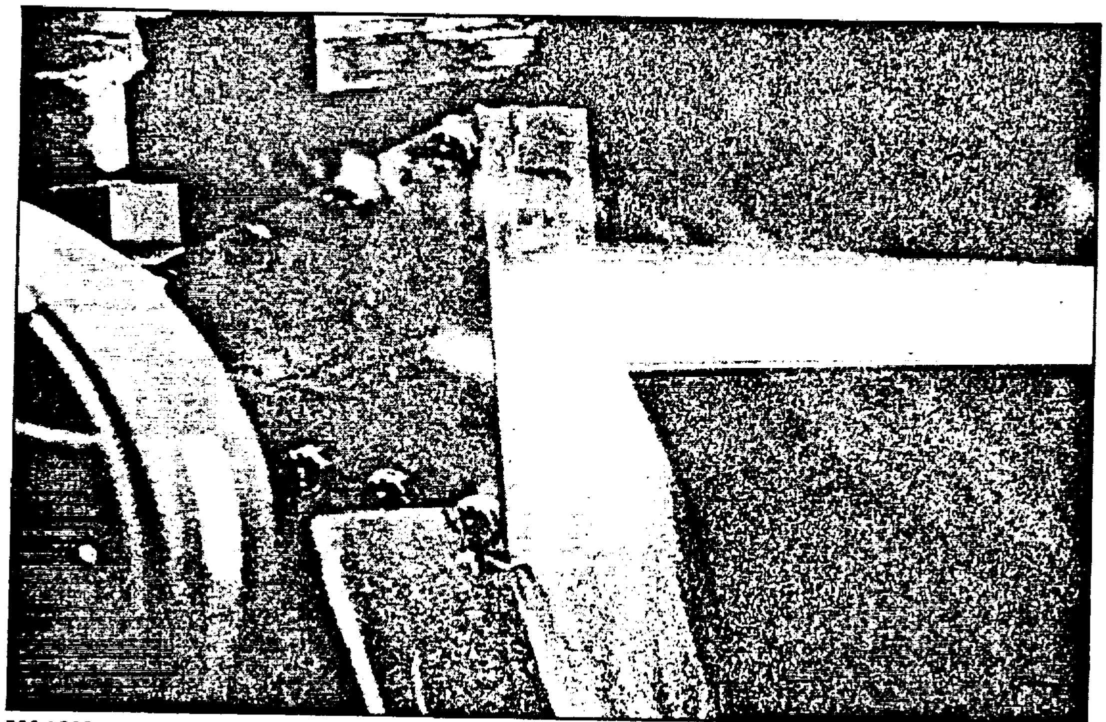


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Fig. 4-1 DROPLET IMPINGEMENT ON COLLECTOR, PUMP OFF

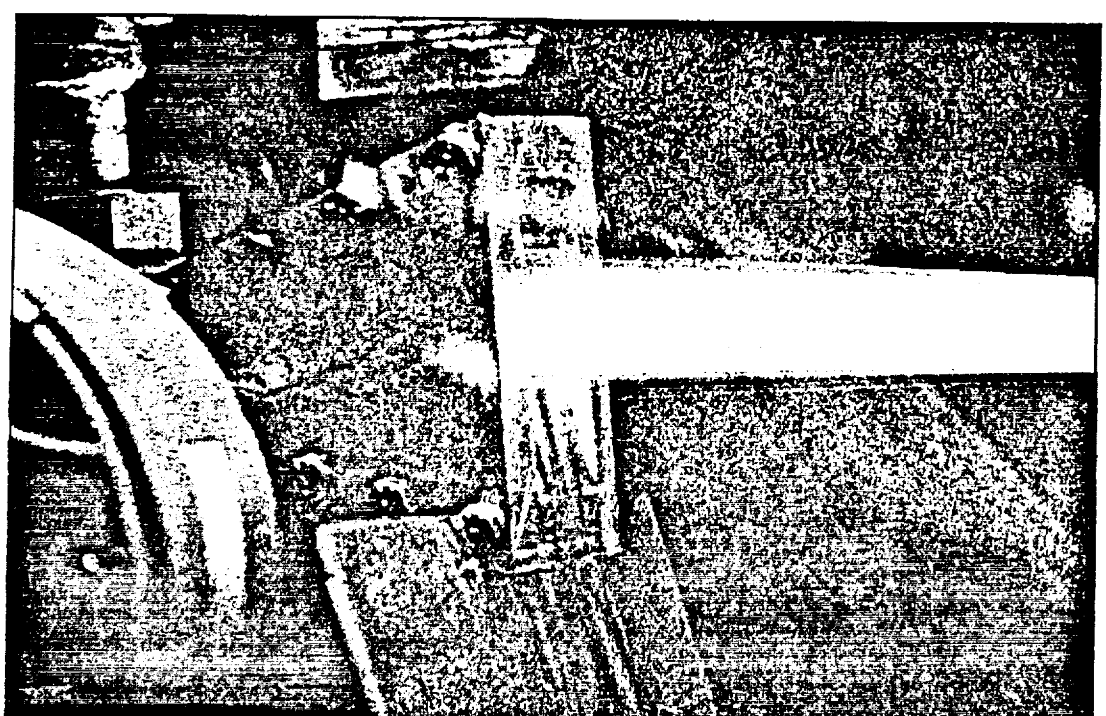

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Fig. 4-2 DROPLET IMPINGEMENT ON COLLECTOR, PUMP ON

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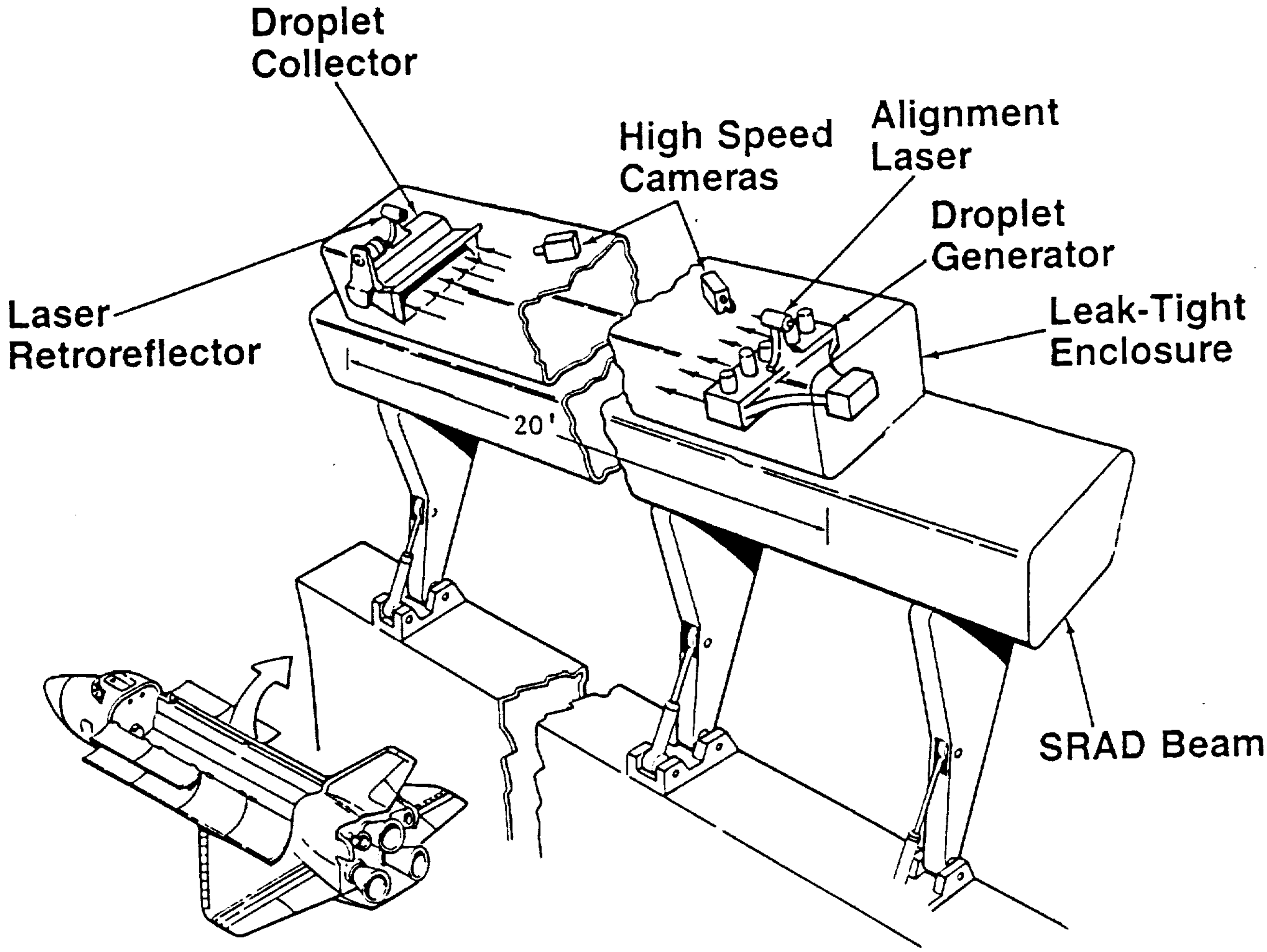

Figure 5 Pictorial of LDR Shuttle Attached Experiment

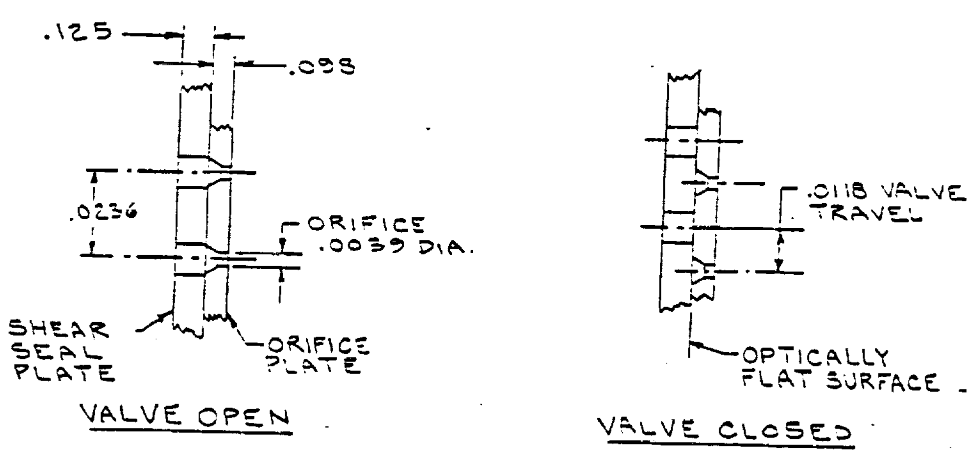

Figure 6 Sketch of Generator Shear Seal Valve

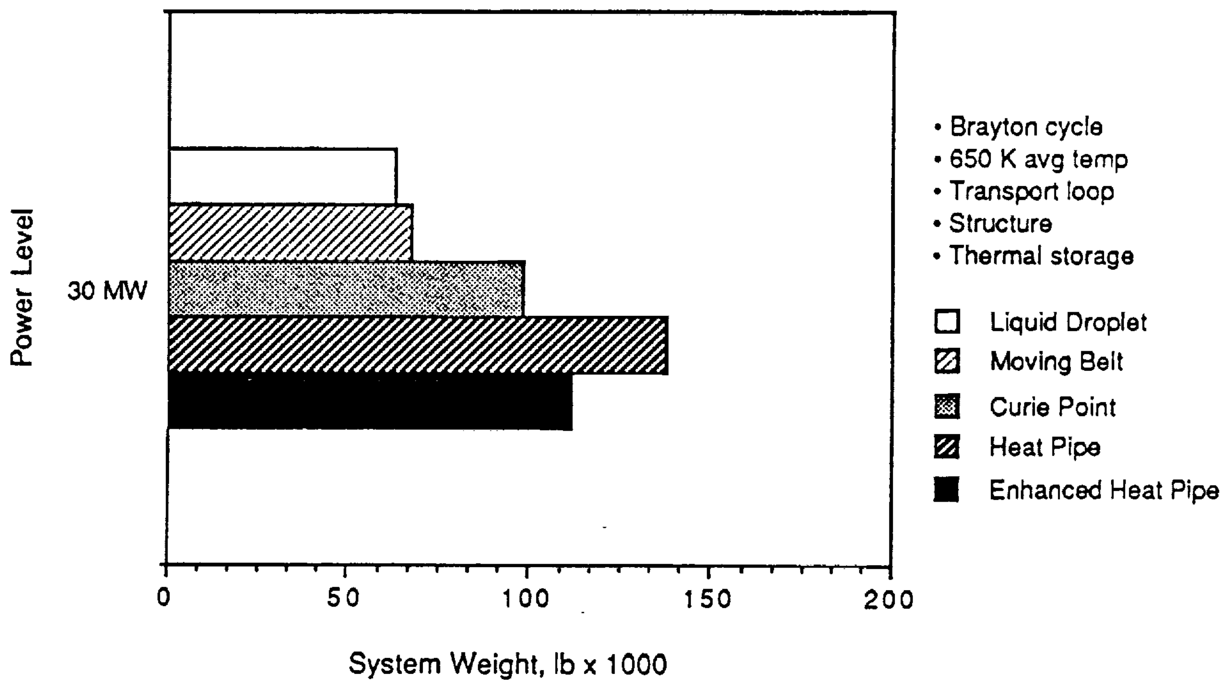

Figure 7 Comparison of Advanced Heat Rejection System Weight

	Heat Pipe Radiator	Enhanced Heat Pipe Radiator	Liquid Droplet Radiator	Moving Belt Radiator	Curie Point Radiator	Rotating Bubble Membrane Radiator
Radiator	47863	36624	12903	14933	30635	106224
Structure	11240	10450	6371	13017	7388	3463
Transport Loop	1484	1484	7008	2607	4400	1796
TES	2086	2086	2086	0	2086	0
Other	0	0	211	0	0	0
Total	62673	50644	28579	30557	44509	116483
Weights in kg						

Figure 8 Heat Rejection System Weight Summary

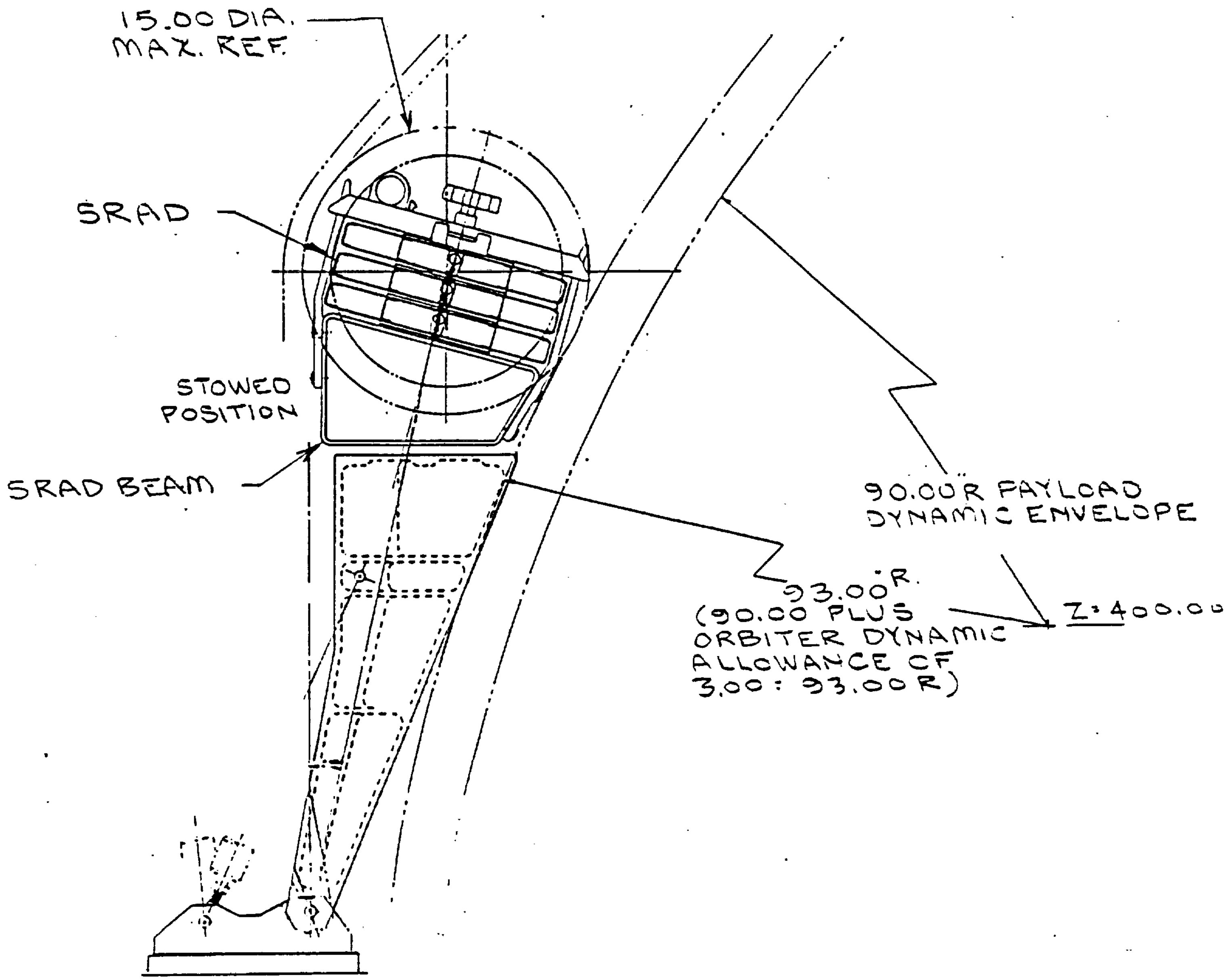

Figure 9   Location of LDR Experiment

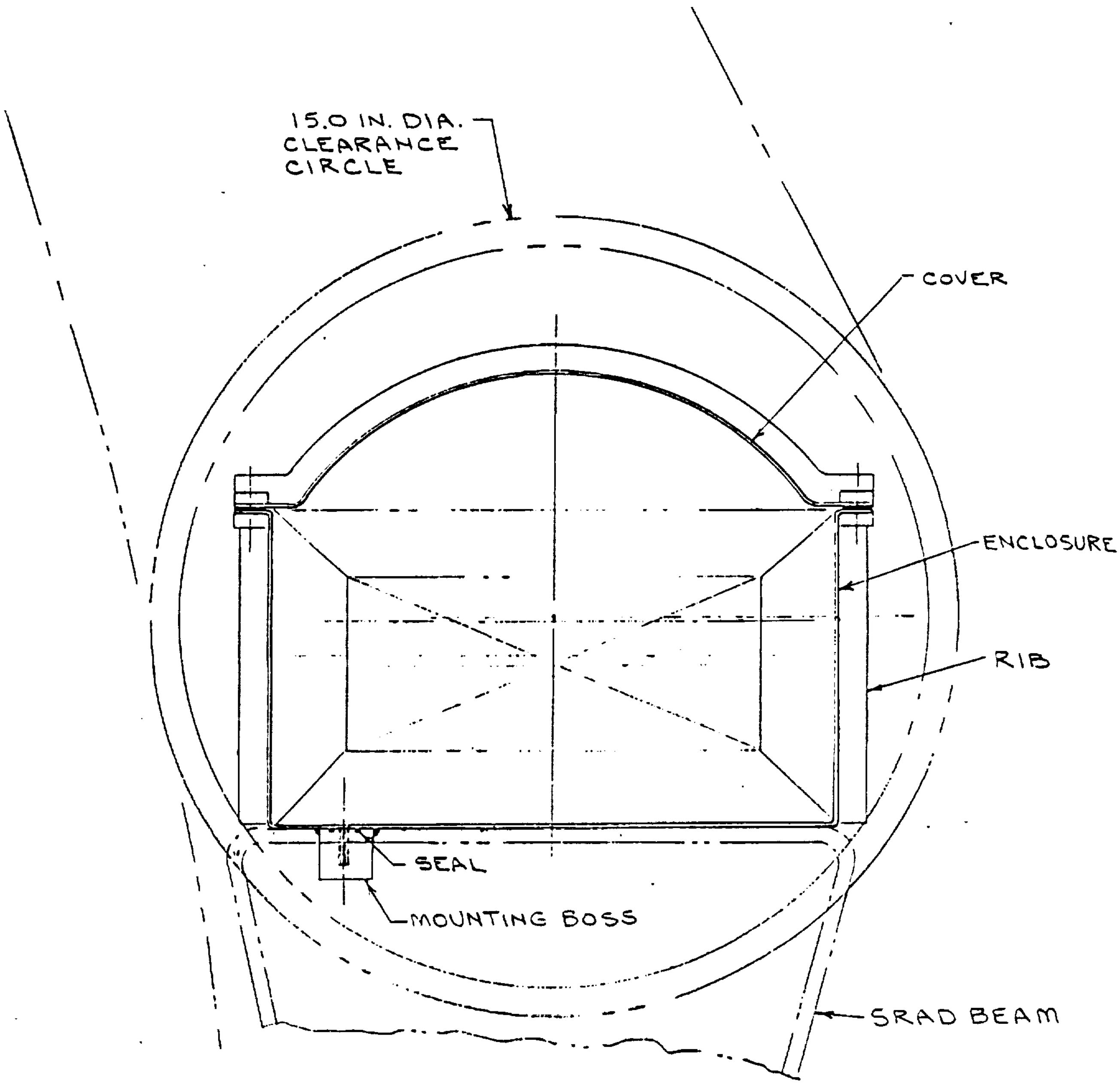

Figure 10 Cross-section of LDR Enclosure

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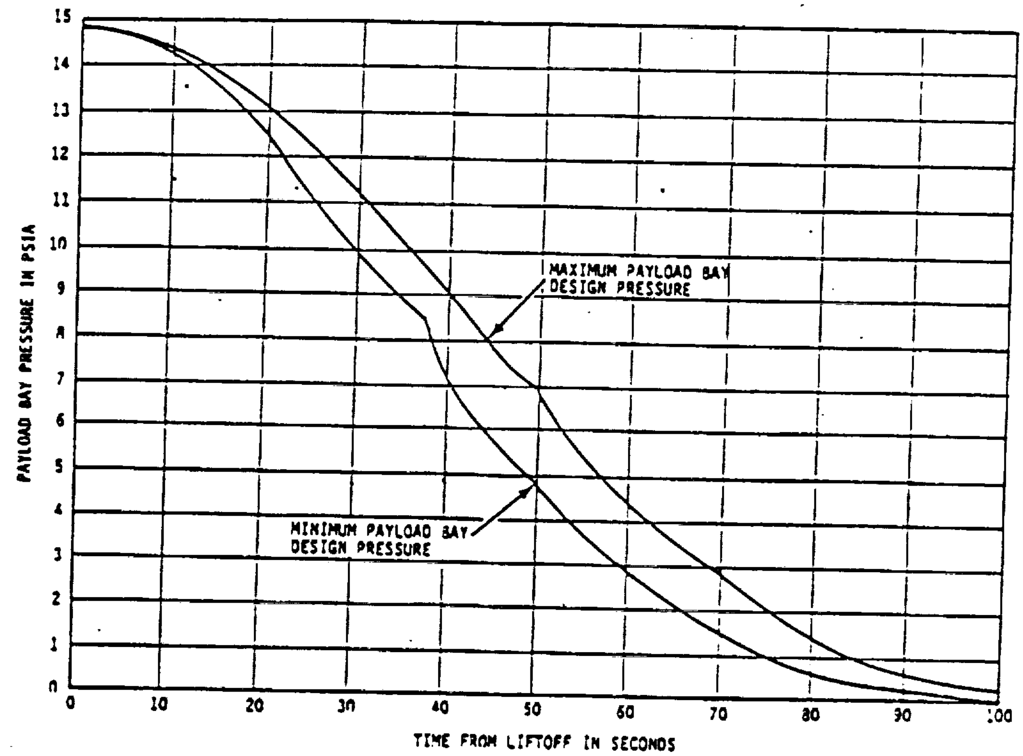

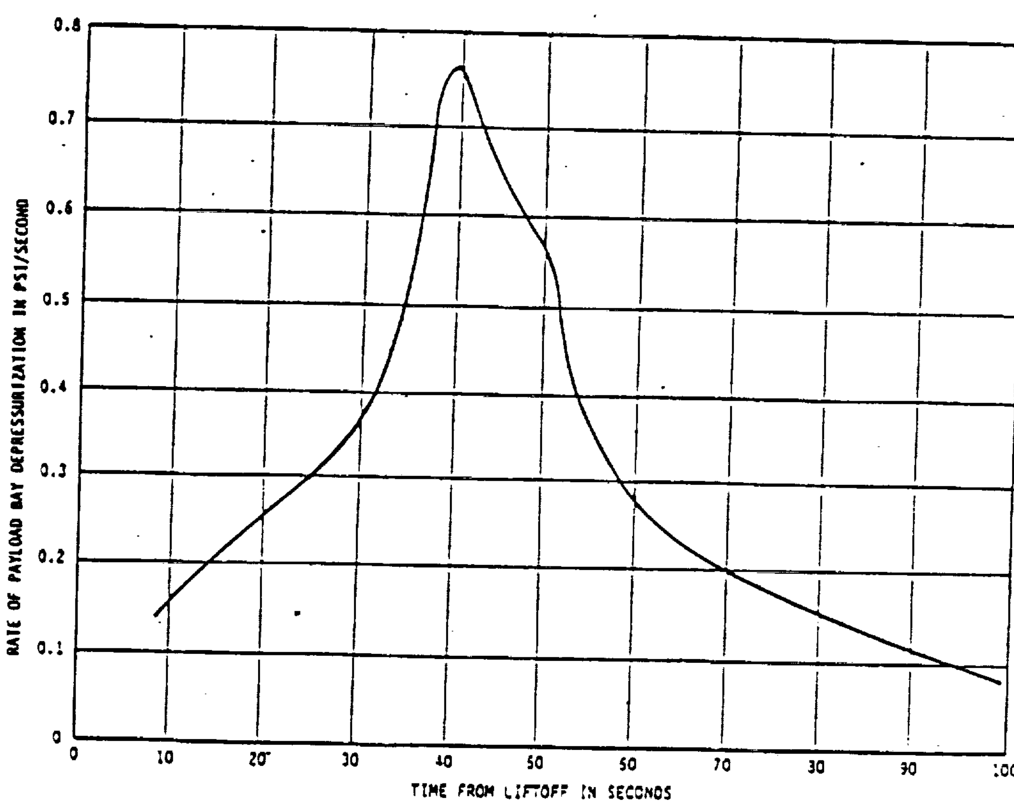

Figure II Pressure History of Shuttle Cargo Bay After Liftoff

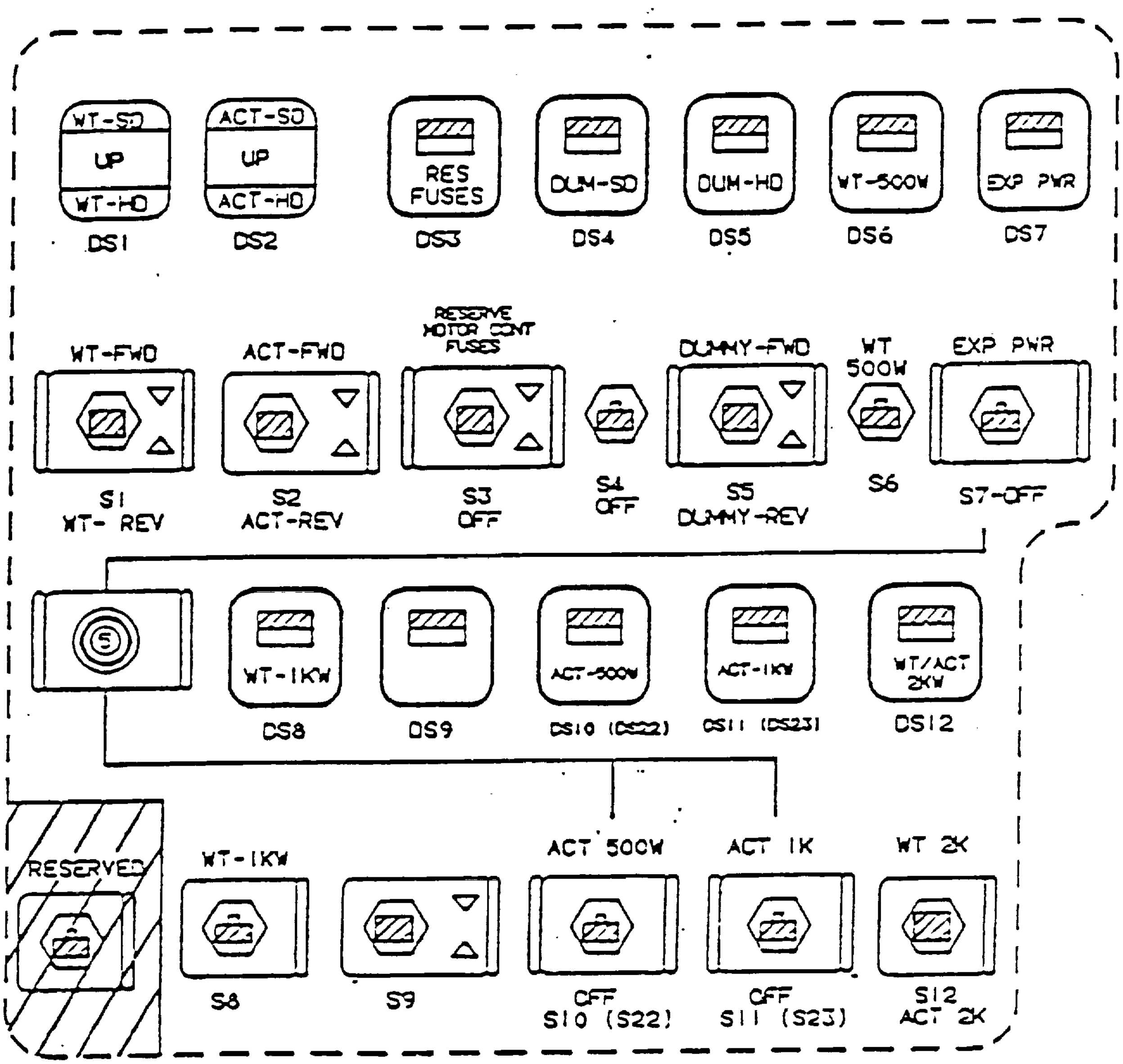

Figure 12 Standard Switch Panel Shuttle-Crew Compartment

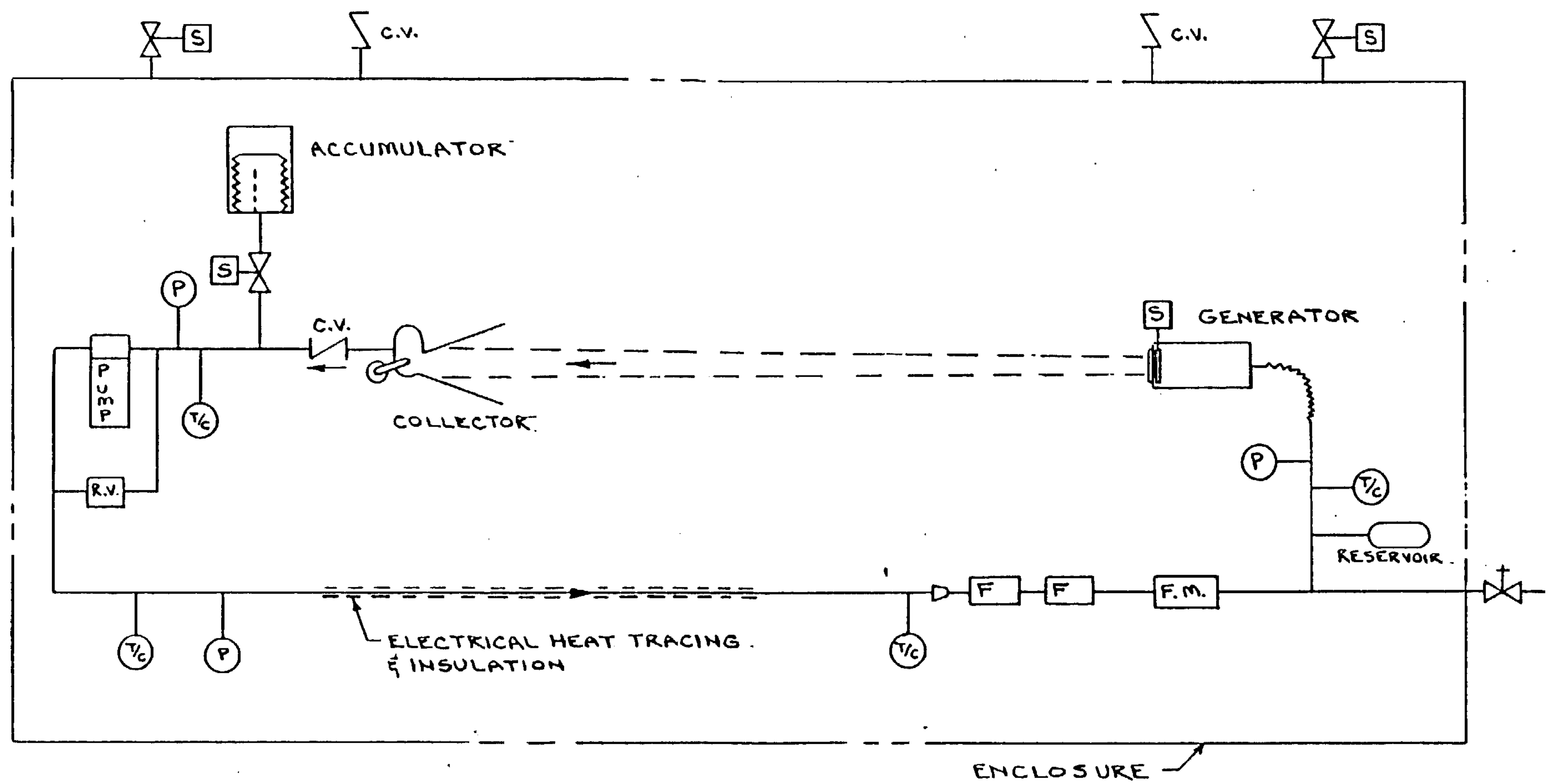

Figure 13 Schematic of LDR Experiment

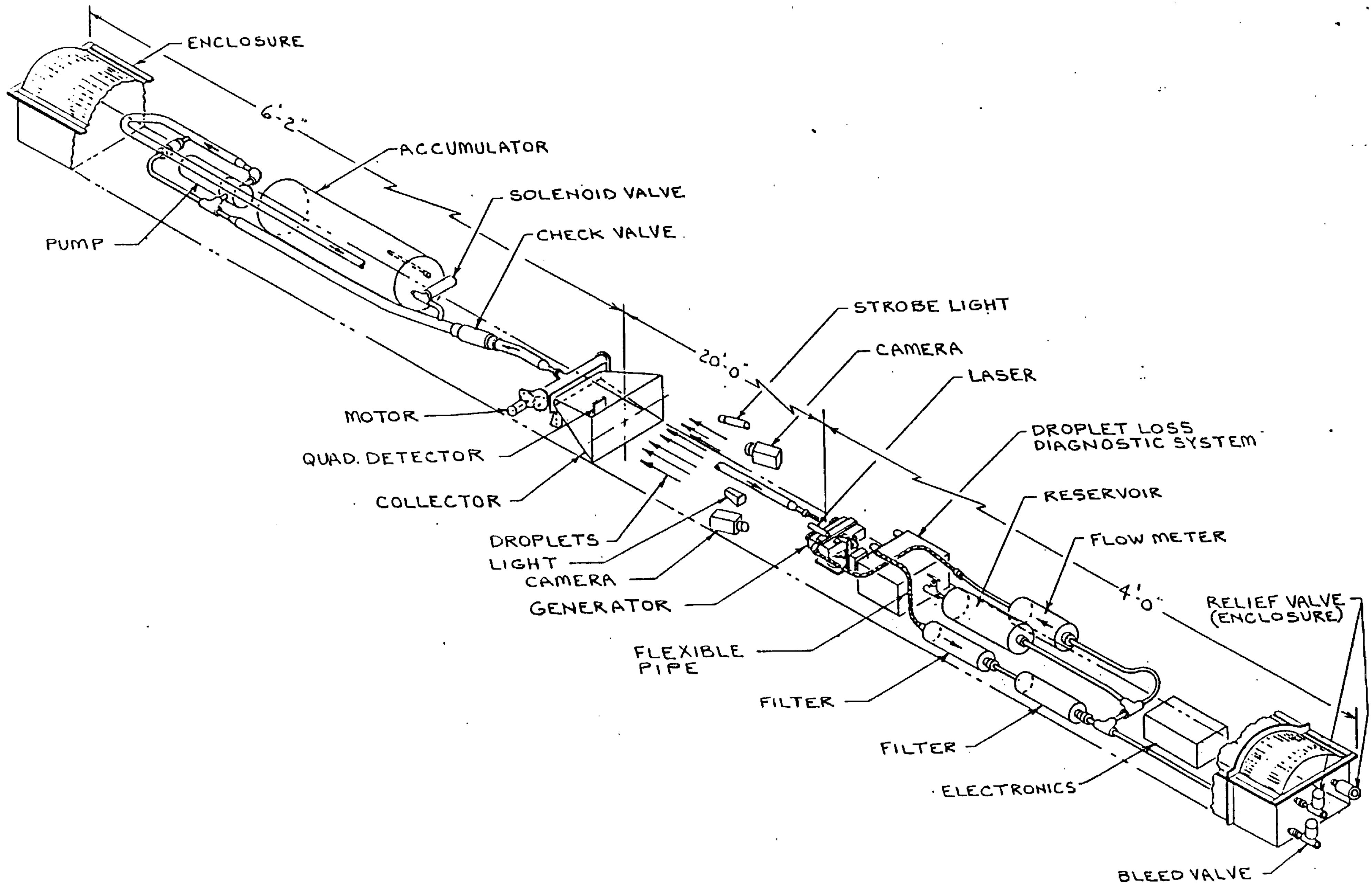

Figure 14 Liquid Droplet Radiator In-flight Experiment

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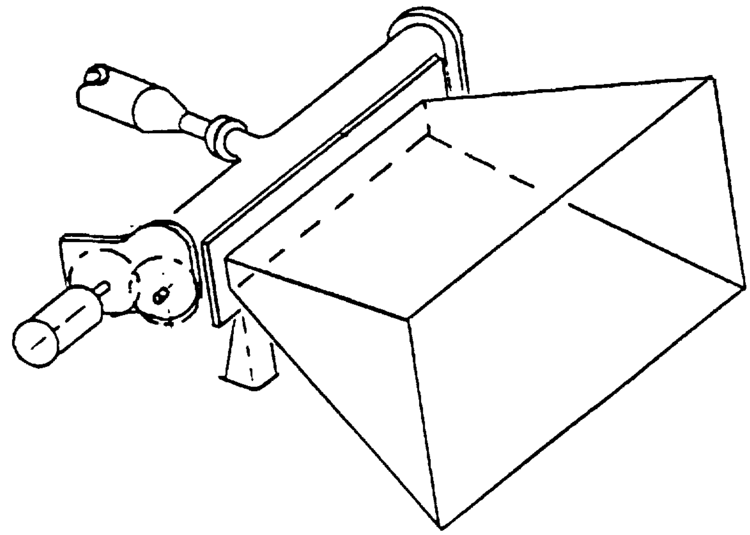

Figure 15 Isometric View of Collector

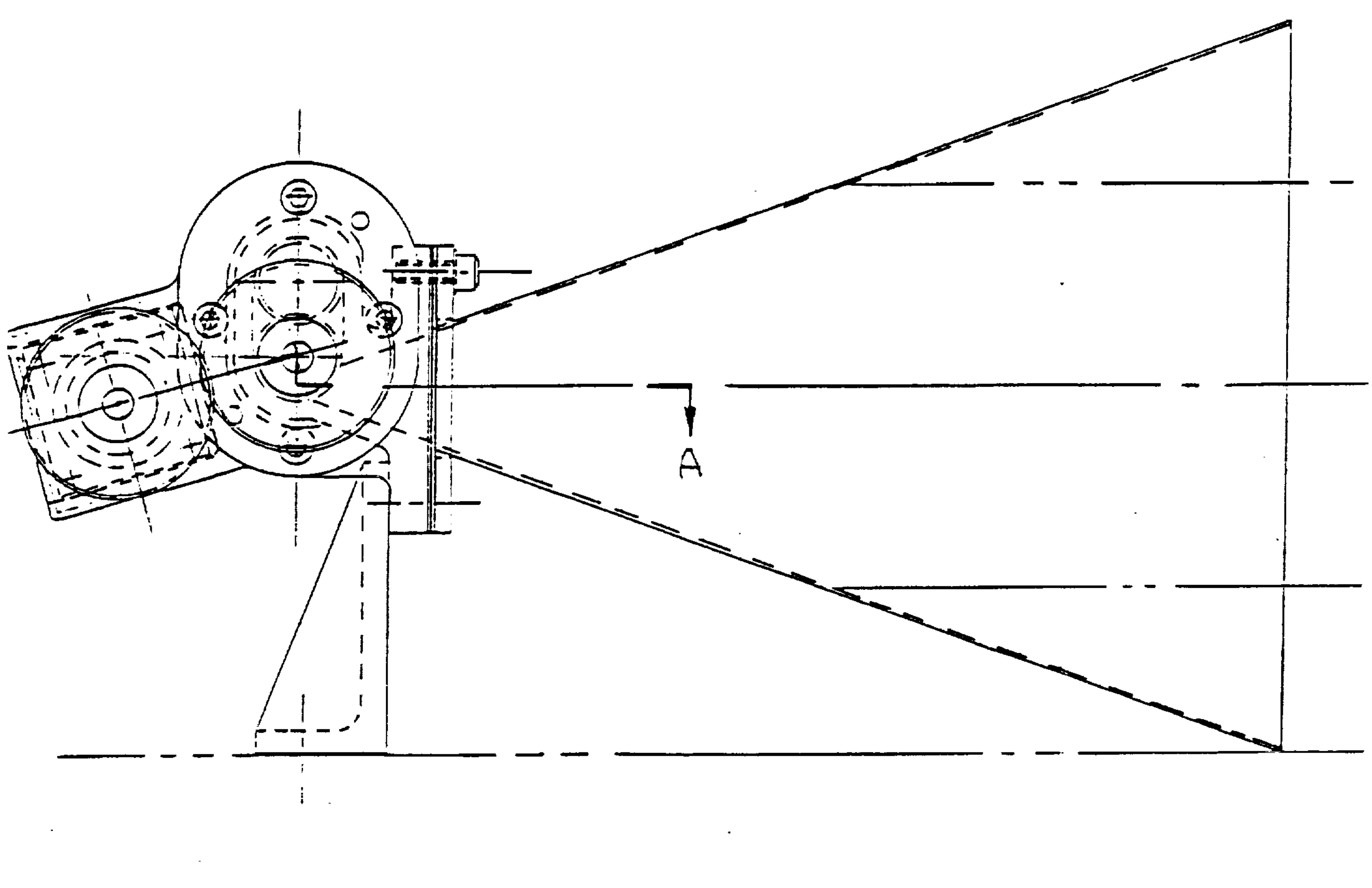

Figure 16 Side View of Collector

Mission	Power Level	Duration
Manned Space Station	30-200 kW	20 yrs
Lasers	1 MW	10 yrs
Particle Beam	1 MW	10 yrs
Space Based Radar	30-100 kW	10 yrs
Lunar Base	100-200 kW	30 yrs

Table 1 Potential Future Space Applications for LDR

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National Aeronautics and Space Administration

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15. Supplementary Notes

PROJECT MANAGER, ALAN WHITE, POWER TECHNOLOGY DIVISION, NASA LEWIS RESEARCH CENTER
IN-SPACE EXPERIMENTS FOCAL POINT, OLGA GONZALEZ-SANABRIA

16. Abstract

The technical requirements of a shuttle-attached Liquid Droplet Radiator (LDR) experiment are discussed. The Liquid Droplet Radiator is an advanced lightweight heat rejection concept that can be used to reject heat from future high powered space platforms. In the LDR concept, submillimeter sized droplets are generated, pass through space, and radiate heat before they are collected and recirculated back to the heat source. The LDR experiment is designed to be attached to the shuttle longeron and integrated into the shuttle bay using standard shuttle/experiment interfaces. Overall power, weight, and data requirements of the experiment are detailed. Shuttle integration and safety design issues are discussed. An overview of the conceptual design of the experiment is presented. Details of the conceptual design are not discussed here, but rather in a separate Final Report.

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