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Liquid Droplet Radiator Program at the NASA Lewis Research Center

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LIQUID DROPLET RADIATOR PROGRAM AT THE NASA LEWIS RESEARCH CENTER

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SUMMARY

The NASA Lewis Research Center and the Air Force Rocket Propulsion Laboratory (AFRPL) are jointly engaged in a program for technical assessment of the Liquid Droplet Radiator (LDR) concept as an advanced high performance heat rejection component for future space missions. NASA Lewis has responsibility for the technology needed for the droplet generator, for working fluid qualification, and for investigating the physics of droplets in space; NASA Lewis is also conducting systems/mission analyses for potential LDR applications with candidate space power systems.

For the droplet generator technology task, both micro-orifice fabrication techniques and droplet stream formation processes have been experimentally investigated. High quality micro-orifices (to 50 μm diameter) are routinely fabricated with automated equipment. Droplet formation studies have established operating boundaries for the generation of controlled and uniform droplet streams. A test rig is currently being installed for the experimental verification, under simulated space conditions, of droplet radiation heat transfer performance analyses and the determination of the effective radiative emissivity of multiple droplet streams. Initial testing has begun in the NASA Lewis Zero-Gravity Facility for investigating droplet stream behavior in microgravity conditions. This includes the effect of orifice wetting on jet dynamics and droplet formation. The mission analyses are identifying integration requirements for the LDR with solar and nuclear power systems. Results for both Brayton and Stirling power cycles have identified favorable mass and size comparisons of the LDR with conventional radiator concepts.

The objective of the program tasks is to resolve critical technology issues which confront the development and design of a prototype LDR system for testing in space environment. An essential part of the current technical program pertains to the experimental investigation of multistream dynamics and thermal behavior for the droplet sheet mass in simulated space environment.

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INTRODUCTION

An advanced radiator concept, the Liquid Droplet Radiator (fig. 1), has recently been studied because of its potentially significant weight reduction benefits for space power systems (refs. 1 to 3).

NASA and the Air Force have embarked on a cooperative program to determine the potential system capabilities of the LDR concept, and to assess its technical feasibility for NASA and Air Force missions. Table I shows that agency responsibility is divided along the major subsystems. The evaluation program provides all elements necessary to future space tests: resolution of critical issues, establishment of performance and other characteristics, incorporation of Air Force and NASA mission analyses, and proof-of-concept tests under simulated space conditions.

The NASA Lewis Research Center program for LDR technology development is presently within Tasks I, II, and V. The subtasks, shown in figure 2, represent critical technical issues that Lewis Research Center is currently addressing. The present paper is a status report on those task projects.

Task I. Liquid Droplet Generator Development

The radiating droplet streams (fig. 1) are created by the droplet generator. The requirements of the radiating sheet of droplets, with tens of thousands of streams of uniform droplets, and with no stream deviating more than 2 to 3 mrad, places severe requirements on the performance of the generator module. Figure 2 shows that at NASA Lewis, study of the droplet generator consists of two interrelated subtasks: orifice fabrication technology, and droplet formation technology.

<u>Orifice fabrication technology</u>. - Identification or development of fabrication methods for micro-orifices is a major focus of the NASA Lewis program. Several orifice-fabrication techniques were assessed for their ability to meet the LDR requirements. Fabrication of orifices with diameters in the 25 to 250 μm range is necessary, with orifices being of satisfactory quality to ensure accurate jet trajectories. Adaptability of the fabrication technique to the production of thousands of holes is also required. The fabrication methods investigated were electro-discharge machining, laser drilling, electrochemical milling, and mechanical drilling.

Electro-discharge machining has been used to fabricate tens of thousands of orifices on a production basis (ref. 4). However, current technology is limited to fabrication of holes larger than 300 μm. Laser drilling of orifices can also be accomplished on a production basis (ref. 5). Sample laser-drilled orifices fabricated for NASA Lewis were of poor quality, and orifices could not be drilled in sufficiently thick stock. Similar problems occurred with electrochemically-milled orifices.

Ink-jet printer requirements (ref. 6) are somewhat similar to those for LDR droplet generators. Some ink-jet printers have orifices that have been etched on a silicon substrate (ref. 7). That fabrication method does not yield an orifice plate rigid enough to meet LDR requirements.

Extensive work has been done at NASA Lewis on development of mechanically-drilled orifices. Similar work is being pursued by a textile firm with extensive experience in extrusion of ultrafine cellulosic fibers. Development of micro-orifice drilling has progressed steadily in the NASA Lewis machine shop. Fabrication of orifice diameters from 25 to 250 μm is routine, and orifices have been drilled in aluminum, magnesium, tungsten, and 316 SS. Arrays have ranged from single- to 900-hole orifice plates, the latter formed in a 3 by 1.5 cm rectangular pattern. Recent installation of computer programmed machining equipment has greatly improved the accuracy and quality of the drilling.

While the principal development goal has been to fabricate orifice plates with parallel stream patterns, a secondary emphasis has been to identify orifice geometries with high volume-discharge coefficients. Figure 3 shows several orifice cross sections that have been investigated experimentally. Orifice tests were conducted using a diffusion pump oil (DC-704), with a viscosity of 42 cSt at 25 °C. Flow was in the low laminar regime, with maximum Reynolds numbers around 200 for the largest orifices.

Straight cylindrical holes had unacceptably low discharge coefficients, and were troublesome to produce due to the necessity of milling the plate in the vicinity of the hole. This extra milling was necessary, as the small drills were limited to a maximum penetration of ten diameters.

Thicker and structurally sounder plates were fabricated using tapered (countersunk) entrances to the final orifice diameter. The knife edged and chamfered holes shown in figure 3 are variants of that method. The knife edged plates showed the largest discharge coefficients (about 0.75), but trajectory control was unreliable. The ASME flow nozzles, the double chamfered orifices, and those with protruding lips were briefly tested, but were not considered acceptable because of additional machining or tooling problems.

Most work has concentrated on the single chamfered geometry, with a short cylindrical capillary after the conical entrance. Development has focused on improving the stream-to-stream parallelism of multi-hole arrays of this configuration. The computer-numerically-controlled (CNC) drilling machine, with a positioning accuracy of microinches, was required to produce arrays having milliradian dispersion accuracy. The drilling equipment requires a constant temperature and humidity environment in order to stabilize positioning of the drill. Experience has shown that aligning the drill bit to accuracies of one or two microinches, with respect to the already drilled conical entrance, is essential for further quality improvement.

Surface finish of the orifice plate is also important. Burrs on the edge of the hole will cause trajectory problems. Test fluid wetting of the plate on the discharge side can also misalign the stream, especially at low jet velocities, due to partial attachment of the stream to the film. Several nonwetting coatings, TEFLON[1] and FREKOTE[1], have been successfully applied to aluminum orifice plates. These coatings eliminated the adverse wetting effects. However, an acceptable fabrication procedure for drilling through coated plates is still under investigation.

Droplet formation technology. - The generation of uniformly sized and spaced droplet streams has been investigated concurrently with the fabrication of the micro-orifices. Although jet breakup and droplet formation have been studied both analytically and experimentally for over a century, it is still an active area in research and technology development.

Figure 4 shows the droplet generator used at NASA Lewis to study the formation of uniformly-sized and spaced streams of droplets. The experiments are usually performed within a vacuum bell jar. Primary measurements of droplet size and spacing are made by 35 mm high speed photography. The piezoelectric

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[1]Registered

crystal inside the generator head has a harmonic voltage applied to it from an external signal generator. The sound waves induced in the fluid by the pulsed piezo crystal cause the orifice jet to break up into uniform droplets at the applied frequency. This phenomenon of forcing jet breakup is well known (ref. 8). The NASA Lewis generator, with DC-704 diffusion pump oil as the working fluid, has worked most efficiently with a square wave input to the piezo crystal. The piezo is a hollow sphere of PZT (lead-zirconate-titanate) ceramic, 0.7 inch diameter, with a natural frequency of about 80 kHz. This sphere is loosely held by a Teflon cradle within the generator head, which is an aluminum cylinder 2.5 (diam) by 2.0 inches. The acoustic waveform sensed by the dynamic pressure transducer in the generator head (fig. 4) has been consistently about 90° out of phase with the signal generator input to the PZT piezo. This confirms that the piezo element is essentially a capacitor drawing almost no power.

The radiant heat transfer analysis of the sheet of droplets sets the specifications on droplet spacing, diameter, velocity, density, and orifice size. As a consequence, a very broad spectrum of droplet formation variables must be investigated. Droplets ranging from 60 to 1000 μm diameter have been generated from single and multiple hole orifices 33 to 200 μm in size. Figure 5 shows an array of five droplet streams from a plate of single chamfered orifices 200 μm in diameter. The frequency and droplet velocity were low, resulting in the large droplets. It will be noticed that the middle stream has a slightly higher velocity than the others, and also that small satellite droplets occur in that stream at random intervals.

For any given orifice, the region of uniform droplet formation has upper and lower bounds on the vibration frequency-droplet velocity plot. Figure 6 shows the experimentally determined domain of acceptable droplet formation for a chamfered orifice 100 μm in diameter. In the frequency-velocity regions outside of the uniform droplet formation domain, the liquid stream breaks up into droplets with a wide dispersion of droplet sizes. An earlier investigation (ref. 9) reported similar behavior in forming drops from the end of a capillary tube which was vibrated at a low sonic frequency.

Multiple droplet stream stability over flight lengths of perhaps tens of meters is of great concern in the LDR development program. At the University of Southern California, single stream stability with no more than a 2 μrad dispersion has been achieved for flight paths of 5.5 m and velocities up to 100 m/s (refs. 8 and 10). Two orifices, 146 and 183 μm diameter, were used; they were etched from sapphire crystals with shape similar to the tapered geometry in figure 3. NASA Lewis will be testing machined multiple hole orifices for stream stability over a 2 to 3 m path as a crucial test of orifice quality and droplet formation technology.

Task II. Radiator Physics and Materials

The radiating sheet of droplets is the working heat transfer surface of the LDR. Optimizing the droplet sheet performance is the ultimate goal of Task II of the joint AFRPL-NASA Lewis program plan. It has several critical technology subtasks: an experimental heat transfer study of droplet sheets to confirm or modify analytical methods of radiation calculations, identification and testing of potential space-compatible working fluids, and an experimental study of droplet stream formation and behavior under microgravity conditions.

Heat transfer studies. - Since the area of a radiator is inversely proportional to its emissivity, the mass advantage of the LDR over heat pipe radiators (1.7 versus 4 kg/m^2) is lost if its emissivity is less than 0.4. (Heat pipe emissivities are about 0.85.) In order to predict the emissivity of the droplet sheet, Hertzberg and Mattick (ref. 1) assume that the droplets behave as opaque gray bodies with isotropic scatter, and that the sheet is isothermal through its thickness. The hemispherical emissivity is determined by using the equations of radiative transfer in an absorbing and scattering plane layer. The solution is expressed by a nonlinear integral equation that was solved numerically. Sheet emissivity is a function of droplet emissivity and optical depth of the sheet. Results are shown in figure 7.

Transmissivity decays exponentially with optical depth. For a body with constant absorptivity, optical depth is the product of absorption coefficient and path length (film thickness or droplet radius). For the LDR, Hertzberg and Mattick define sheet optical depth as $\tau_S = n\sigma S$, where n is the droplet number density per unit volume, σ is the cross-sectional area of a droplet, and S is the thickness of the sheet. With this definition, transmission through a sheet of black droplets decays exponentially with optical depth of the sheet.

Sheet emissivity is dependent on the configuration of the droplet sheet and on intrinsic droplet emissivity. Although droplet emissivity has not been measured directly, normal emissivity of a thin film of DC 704 was measured by Teagan and Fitzgerald (ref. 11) using a Fourier Transform Infrared Spectrometer (FTIR). At a thickness of 0.06 cm, the average film emissivity of DC 704 was 0.95 between 1400 and 400 cm^{-1}. At a thickness of 0.03 cm, the average film emissivity was 0.70 (figs. 8 and 9). This data suggests that the droplet emissivity varies with droplet size for path lengths less than 0.06 cm.

For negligible surface reflectivity, emissivity is one min the transmissivity. At small optical depths, and at normal incidence, transmissivity is approximately linear with optical depth, and emissivity is proportional to path length. It has been suggested that the power to mass ratio of a sphere may be made arbitrarily large by decreasing the radius. In the optically thin limit, however, droplet emissivity is linearly proportional to radius so that this is no longer the case.

When particles are large relative to the wavelength of radiation considered, Mie scattering can be neglected and ray tracing analysis allows expression of the particle emissivity as a function of optical constants and geometry. Hoffman and Gauvin (ref. 12) report expressions for the absorptivity (emissivity) of a sphere as a function of absorption coefficient K, refractive index m, and radius r derived using geometric optics. Results are plotted in figure 10.

As can be seen in the figure, droplet emissivity increases with the product of absorption coefficient and radius. At a value of 3.0, the increase in emissivity levels off. This provides a practical upper limit on droplet diameter much the same way that the optically thin limit provides a lower limit for droplet diameter.

A refined analysis of droplet emissivity would consider the variation of absorption and scattering coefficients with frequency, ν. An iterative procedure allows determination of these coefficients from absorption measurements of thin films in the infrared. Graf, Koenig, and Ishida (ref. 13) have reported the method. The apparent absorptive index, $k(\nu)$, is calculated from the experimental absorption spectrum. The Kramers-Kronig integral relates the refractive index and the absorptive index so that an apparent refractive index, $n(\nu)$, is obtained. The absorption spectrum is then calculated using these trial values for $k(\nu)$ and $n(\nu)$. It is compared to the experimental spectrum and a refined estimate of $k(\nu)$ is made. The process is iterated until agreement between the experimental spectrum and the calculated spectrum is good.

Software from Graf et al. is currently being installed to perform this analysis on a VAX 11/750 computer. A communications link between the computer-run FTIR and the VAX is being selected. Data from FTIR analysis of the absorption spectra of diffusion pump oils will be analyzed in this way.

The predictions of sheet emissivity will be evaluated by measuring a sensible heat loss from the droplet sheet and equating it to the net radiation loss from the sheet to its surroundings. A heat transfer rig is being fabricated (schematic shown in fig. 11) to make these measurements. The rig has a maximum flow rate of 5 gal/min allowing testing of optical depths up to 0.4. The test fluid can be preheated in the supply tank up to 150 °C; however, the likely upper temperature is 70 °C to keep the vapor pressure of the test fluid low. The droplets fall through a liquid nitrogen jacketed vacuum chamber. Although maximum vacuum capability is 10^{-6} torr, expected operation will be at 10^{-4} torr to minimize evaporative heat loss.

The sensible heat loss will be determined from differential temperature measurements of the streams. Temperature probes will translate across the width and depth of the streams to obtain a temperature profile in addition to the average temperature drop. Expected temperature drops are on the order of 2 to 8 °C. Estimated error for the calculated values of sheet emissivity is less than 10 percent.

Working fluid selection. - Potential working fluids for the LDR are categorized according to heat rejection temperature. For solar dynamic or high-temperature nuclear dynamic space power cycles, the LDR will require a liquid metal, while for low temperature "housekeeping" thermal management, fluids similar to organic diffusion pump oils seem to have acceptable properties. The ideal candidate fluid for each of the categories has not been identified.

The most critical fluid requirement is possession of a very low vapor pressure in the applicable temperature range. Figure 12 shows the useful operating range for some liquid metals and one common diffusion pump oil. The maximum allowable vapor pressure of 10^{-9} torr will limit working fluid evaporation in space to a low value.

In addition to the vapor pressure limitation, potential LDR fluids must possess a number of physical and chemical properties reflecting compatibility with the space environment. Additionally, a potential fluid must have other properties to allow for ease of droplet generator and collector operation. Table II lists the important physical and chemical requirements for an LDR working fluid.

An active program at NASA Lewis is focused on identifying low temperature liquids more suitable than the present experimental test fluids. Silicone-based fluids having vapor pressures near 5×10^{-10} torr at 400 K have been synthesized under contract; these represent a 10^{5}-fold decrease in vapor pressure over commercially-available fluids such as DC-705. Further work is in progress to determine the extent to which these fluids meet the other requirements outlined in Table II.

Currently, studies are in progress to determine which molecular structures of low vapor pressure liquids are most resistant to the individual and combined effects of atomic oxygen and ultraviolet radiation. The optimum ranges of viscosity and surface tension are being investigated in conjunction with the droplet formation studies (Task I) at NASA Lewis, and with the droplet collector program at AFRPL (ref. 14). There is no active program at present to investigate corrosion problems.

Zero gravity effects. - Early experiments with the droplet generator (fig. 4) provided evidence that a liquid film initially covering the orifice plate can significantly increase the pressure required to start the droplet stream flow, as well as the lower limiting pressure at droplet stream shutoff. The behavior of an orifice film in space conditions is a serious concern. The long-term effects on droplet stream dynamics can only be examined in actual space flight, e.g., the Shuttle - but much valuable information can be obtained from experiments conducted in ground-based microgravity facilities.

In the NASA Lewis Zero-Gravity Facility, a test rig is subjected to over 5 s of microgravity fall at 10^{-5} to 10^{-6} g. This is sufficient time to identify behavior patterns in free-surface fluid films subjected to microgravity.

Figure 13 shows the experimental drop package being fabricated for the NASA Lewis Zero-Gravity tests. The rig is a drop bus containing the droplet generator unit and its associated instrumentation and power package. The droplet streams are contained within a clear plastic pipe to avoid any accidental contamination of the optical instruments.

Figure 14 is a sketch of the experimental rig illustrating in more detail the position of the generator in testing for orifice film effects. The droplet stream flows "up" relative to normal gravity. A precise amount of working fluid can be placed over the orifice prior to package release and flow startup. High speed motion picture cameras record the stream generation-orifice film interactions, as well as the droplet stream impact on the collector at the top of the bus. Two cameras at right angles, with scales in focus behind the drops, will document trajectory accuracy at the collector.

The working fluids will be the diffusion pump oils used in the Task I generator studies. Test parameters and variables are the orifice size and shape, the orifice film depth, the applied pressure, and the volumetric flow during test.

On completion of buildup, the drop package will undergo ground testing and calibration before any microgravity drop tests are permitted. The first drop is planned for November, 1985.

Task V. Mission and Systems Analysis

The Mission and Systems Analysis (M/SA) for the LDR is a concomitant effort with the experimental technology development and demonstration tasks. The objectives of the M/SA Task are to determine the benefits and drawbacks of the LDR concept for NASA and DOD missions, to compare the advantages of the LDR over other concepts in mass, size, and cost, and to determine the efficient LDR operating range. The objectives must build upon a basic systems model which sizes and rates the LDR as a heat exchanger at given operating conditions, and which incorporates the component technologies under development in the other tasks of the program.

The basic physics of the LDR has been described by Mattick and Hertzberg (ref. 1). Their heat transfer model for the radiating sheet is being utilized in the NASA Lewis systems model with modification of the space sink temperature to 250 K. The sheet model of Brown and Kosson (ref. 15), based on a Monte Carlo examination of a dispersed droplet system, has a nonuniform temperature profile across the thickness of the sheet. The Monte Carlo model does generally predict somewhat longer droplet flight paths to service a required heat rejection load than does the optical sheet model. For an optical thickness of the order of unity, there are not significant differences in radiative power calculation between the isothermal and Monte Carlo models (ref. 1). An independent effort is analyzing a generalized nonisothermal sheet radiation model in order to determine the conditions for which the deviations become significant between the isothermal and nonisothermal models.

The basic LDR model has been used in designing the in-house heat transfer apparatus. Presently, the models are being expanded to incorporate NASA models of nuclear and solar dynamic power systems. Integration of the LDR with dynamic power systems includes identification of working fluids with operating ranges compatible with the power cycle rejection temperatures. The effects of incorporating a regenerator into power systems utilizing an LDR are being investigated. Although thermal efficiency is higher in regenerated power systems, the additional mass of a regenerator may not be offset by the lower radiator mass of such systems, and total system mass may increase. The lower heat rejection temperature and the lesser amount of waste heat with a regenerator may affect power system optimization differently if an LDR, rather than a conventional radiator, is employed. For instance, the addition of a recuperator on the nuclear dynamic Brayton power system increases the thermal efficiency by 31 percent and decreases the radiator mass. Figures 15 and 16 show the proportion of total system mass attributable to the LDR for four regenerated power systems.

The performance, cost, and reliability of the LDR are also being assessed, for comparison with other radiator concepts. Preliminary results from NASA Lewis computer codes indicate that when coupled with a nuclear Stirling power system, a heat pipe radiator having a surface emissivity of 0.8 is more massive than an LDR with a sheet emissivity of 0.4. Figure 17 shows the total system mass for a 100 kWe nuclear Stirling power plant operating at a hot end temperature of 1050 K. Various performance parameters for the LDR and alternate radiator concepts are under investigation. These include total heat transfer area, overall radiator mass, stowed radiator volume, specific radiative power (heat rejected per unit radiator mass), and unit radiator cost (in dollars per kW rejected). Assessing the relative importance of these parameters will become increasingly important in determining a prototype LDR design.

To more realistically estimate the reliability and performance of the LDR, several effects of the space environment are considered in the LDR system model. Ultraviolet radiation and atomic oxygen can attack the LDR working fluid. Fluid loss can be minimized by selection of a suitable working fluid which is stable in the space environment of the mission. Since the number density, flux, and kinetic energy of atomic oxygen are related to the mission altitude (ref. 16), proper modeling of fluid loss will consider mission altitude. Such a model will consider the effects of variable-energy atomic oxygen on the rate of fluid degradation through oxidation (ref. 17).

More research is needed to investigate the optical property changes when LDR fluids are exposed to atomic oxygen. A dramatic change in chemical composition could adversely affect the optical properties. An appreciable change in optical properties would not only hinder the heat transfer radiating capabilities of the LDR, but would also significantly increase the mass of the LDR. For example, given a nuclear power system, decreasing the fluid emissivity from 0.88 to 0.33 can result in a 54 percent increase in radiator mass and a 16 percent increase in system mass. In-house research efforts at Lewis will aid in the selection of the LDR fluids.

CONCLUSION

The NASA Lewis/AFRPL program plan for the Liquid Droplet Radiator is attacking the technological barriers to the design, development, and testing of a prototype of this advanced radiator concept. All task elements are under investigation. The objective of this first phase of the program is being met: it is anticipated that the resolution of the critical technical issues of the LDR concept will be accomplished by the end of 1986.

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TABLE I. - JOINT NASA-AIR FORCE LIQUID DROPLET RADIATOR PROGRAM

A	Technology development Task I - Liquid Droplet Generator (NASA) Task II - Liquid Droplet Radiator physics and materials (NASA) Task III - Liquid Droplet Collector (Air Force)
B	Design and fabrication Task IV - Test system (Air Force)
C	Analysis Task V - Mission and systems analysis (NASA/Air Force)
D	Proof of concept Task VI - Technical assessment (NASA/Air Force)

TABLE II. - LDR WORKING FLUID REQUIREMENTS

• Space compatability		
	Vapor pressure	- Less that 10^{-9} torr to minimize evaporation losses.
	Optical properties	- Low absorptivity to solar radiation (near IR) to minimize solar heating.
		- High emissivity in far IR for optimum radiator cooling.
	Chemical properties	- Resistant to chemical reaction by energetic (5 eV) atomic oxygen resulting in molecular changes to fluid.
		- Resistant to ultraviolet absorption which can enhance oxygen reaction.
• Generator/collector compatability		
	Viscosity	- Low to minimize fluid pressure losses in generator, collector, and pumps.
	Surface tension	- High for rapid droplet formation.
		- Low to inhibit wetting of orifice and collector surfaces.
	Chemical properties	- Negligible corrosion of collector and generator.

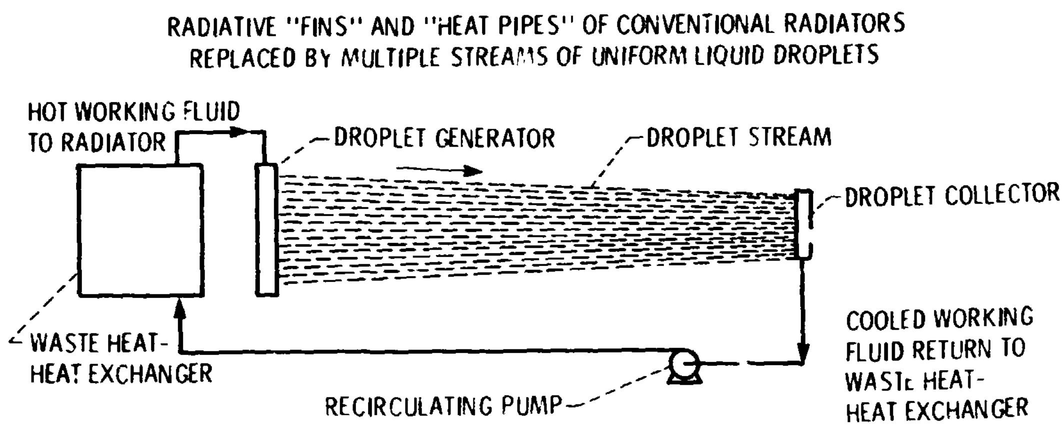

Figure 1. - Liquid droplet radiator concept.

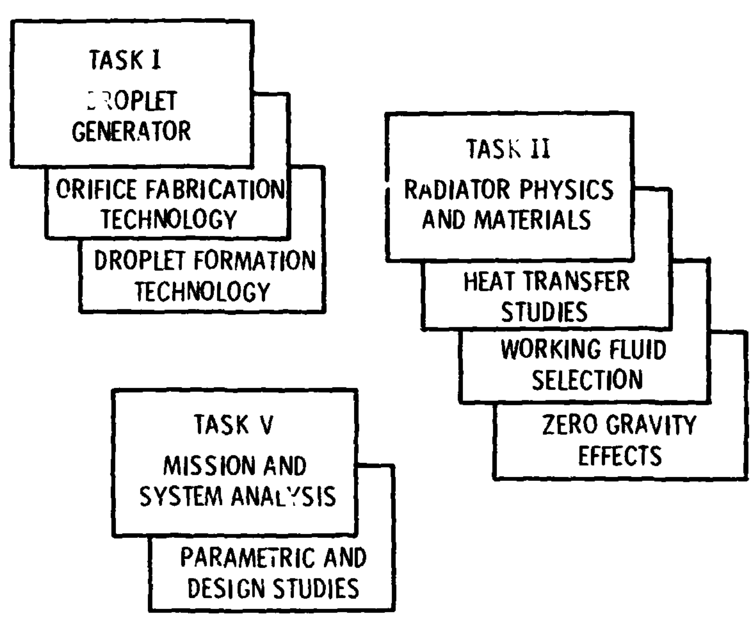

Figure 2. - NASA Lewis LDR program.

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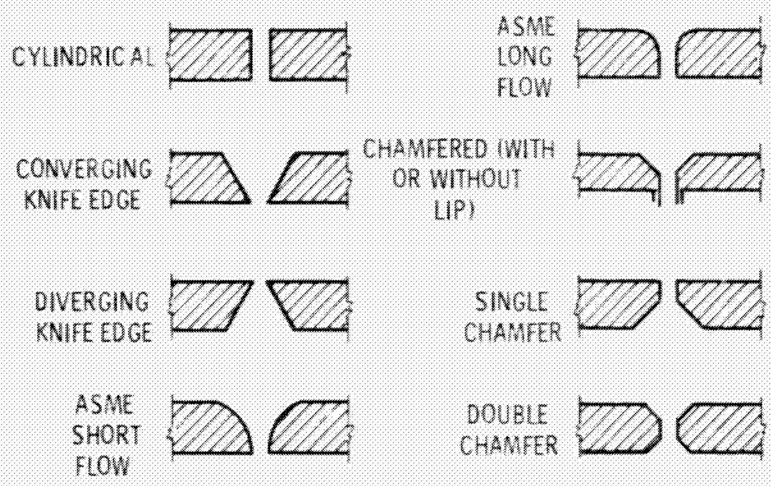

Figure 3. - Experimental orifice geometries.

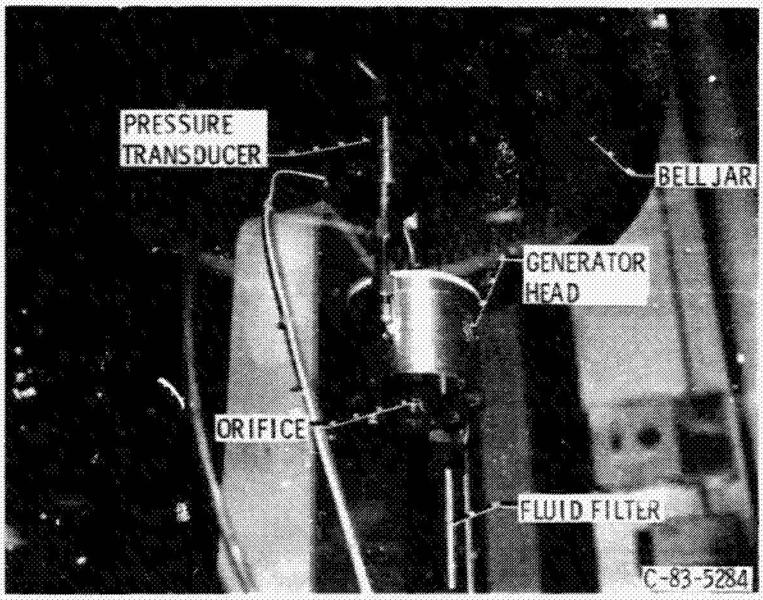

Figure 4. -Experimental liquid droplet generator.

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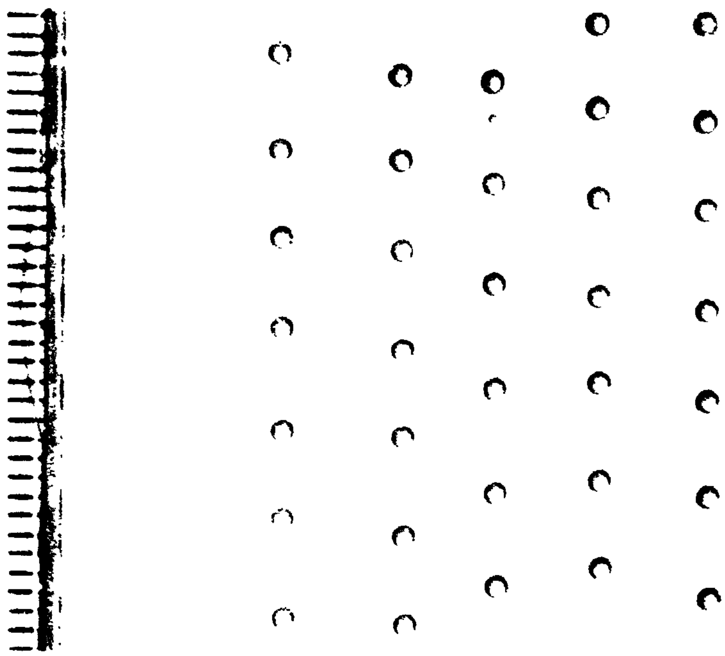

Figure 5. - Droplet streams (1 kHz piezo frequency, 2.5 m/s droplet velocity, 620 ± 25μm droplet diameter)

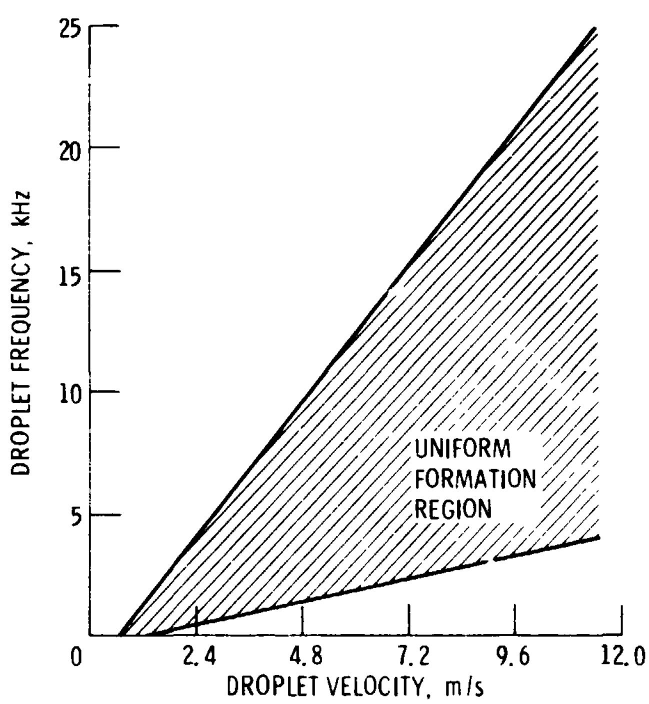

Figure 6. - Experimental frequency-velocity envelope for uniform droplet formation.

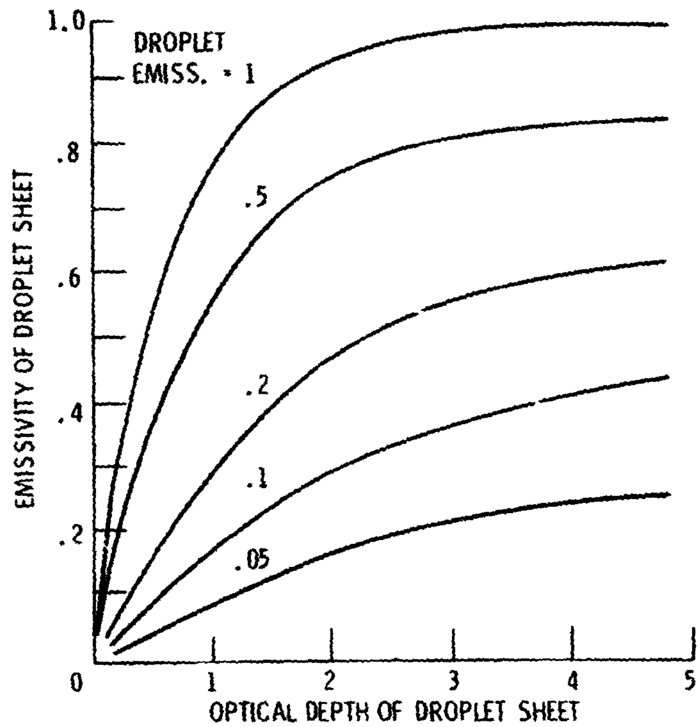

Figure 7. - Hemispherical emissivity of liquid droplet radiator. (ref. 1).

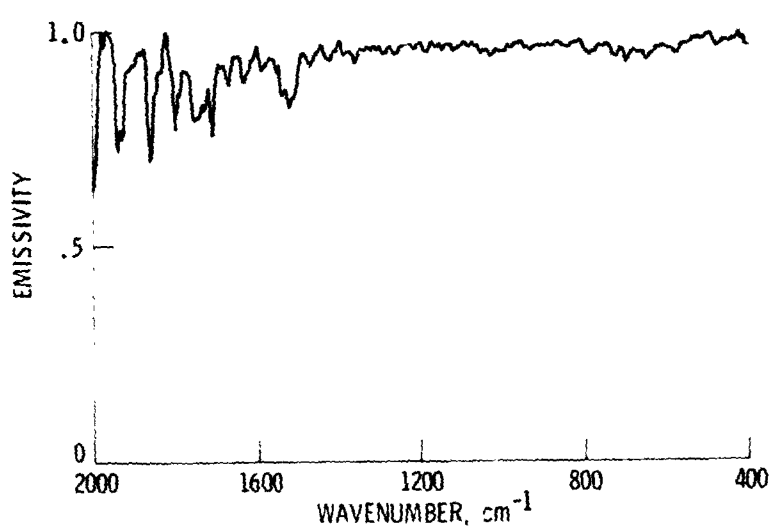

Figure 8. - Normal emissivity of a 0.06 cm thick film of DC 704. (ref. 11).

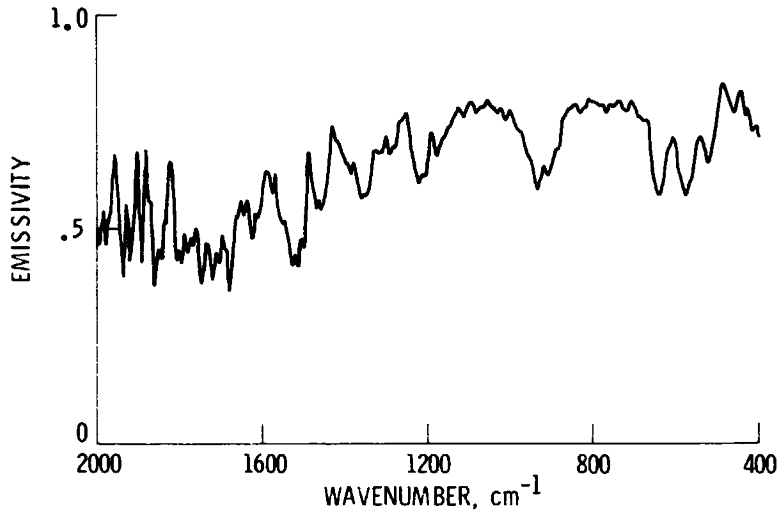

Figure 9. - Normal emissivity of a 0.03 cm thick film of DC 704. (ref. 11).

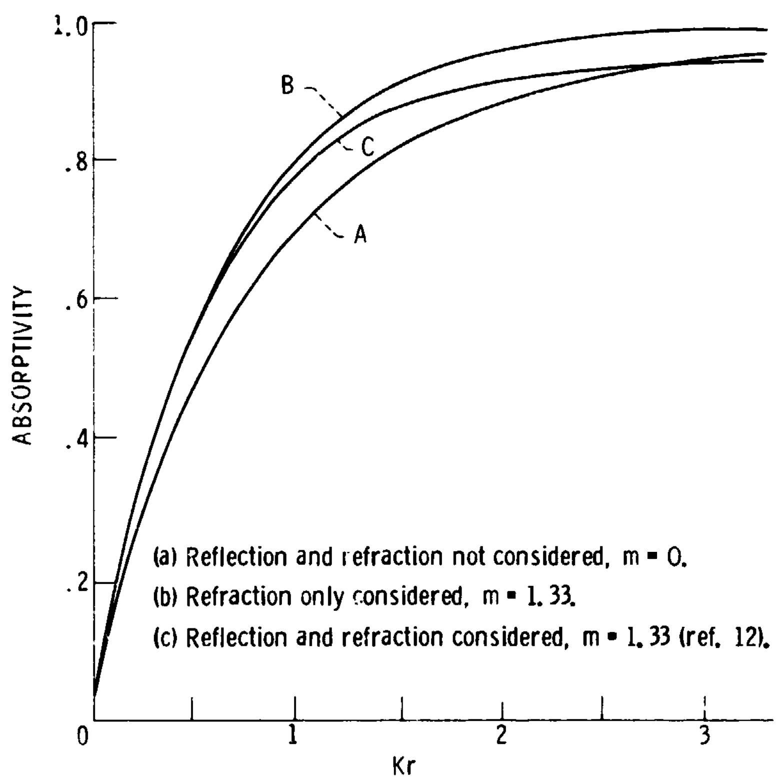

Figure 10. - Absorptivity of a sphere as a function of optical depth.

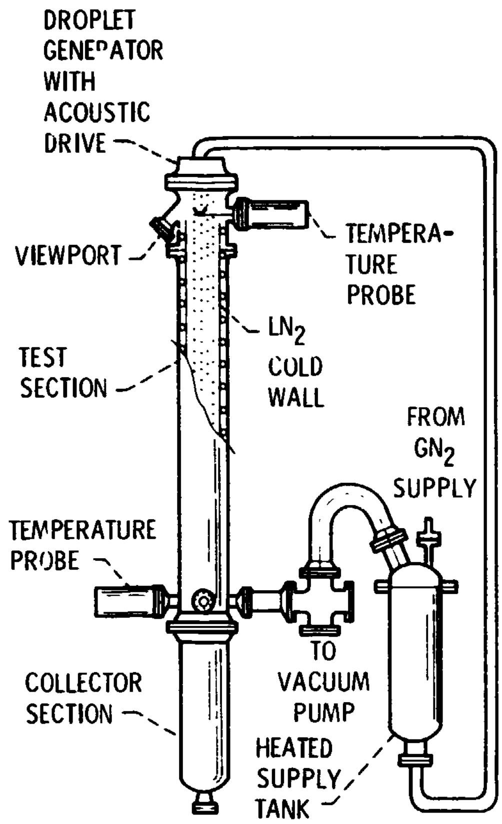

Figure 11. - Test rig flow loop for LDR heat transfer studies.

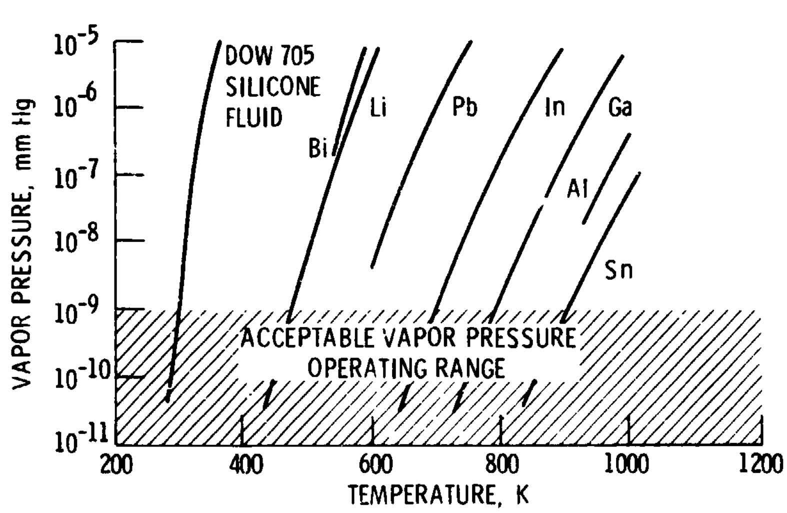

Figure 12. - Vapor pressures of candidate radiator fluids.

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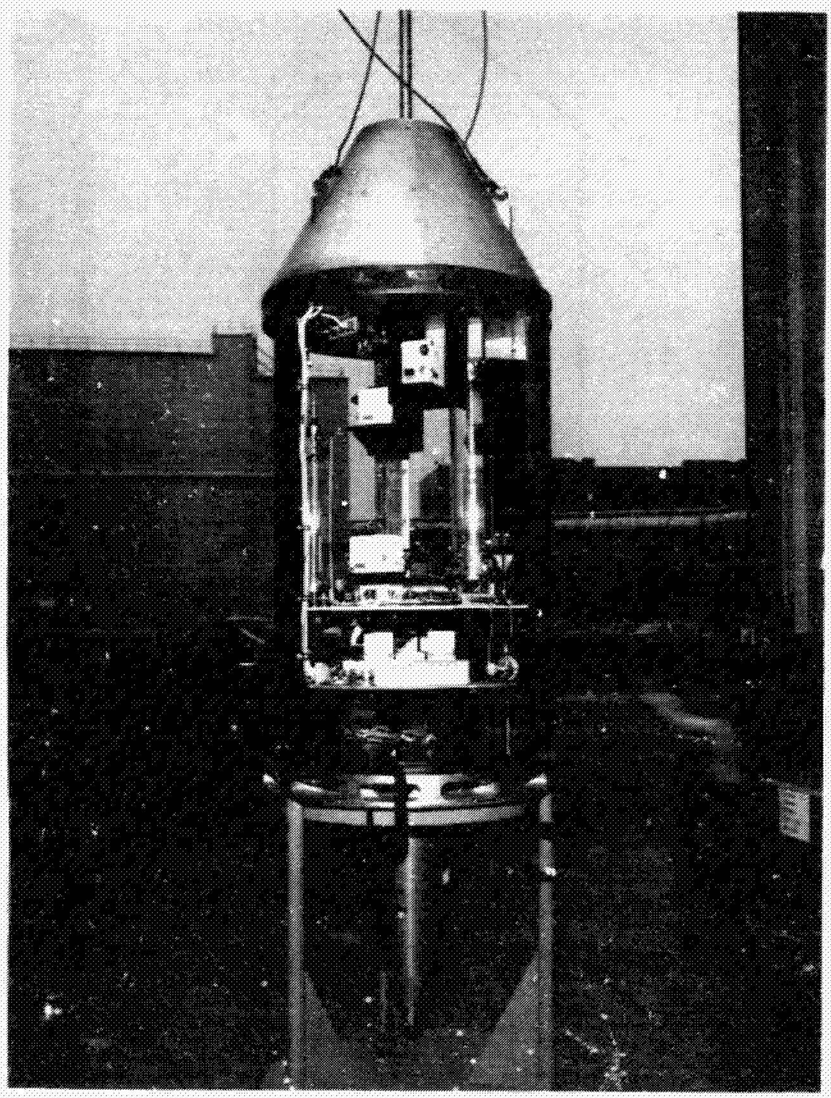

Figure 13. - Drop package in NASA Lewis Zero Gravity Facility.

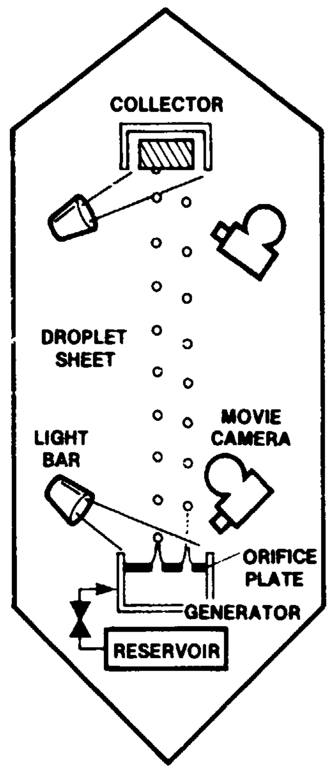

Figure 14. - Zero-gravity experiment.

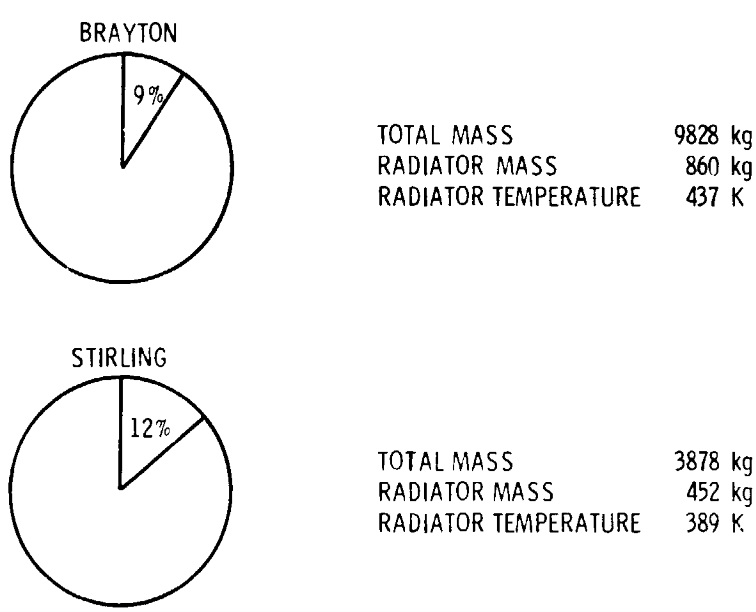

Figure 15. - LDR mass for 100 kW_e solar dynamic power systems.

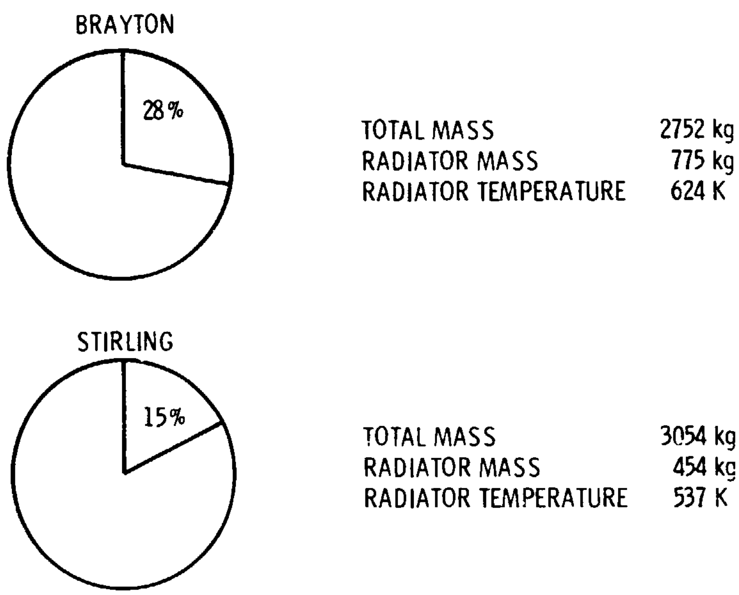

Figure 16. - LDR mass for 100 kW_e nuclear dynamic power systems.

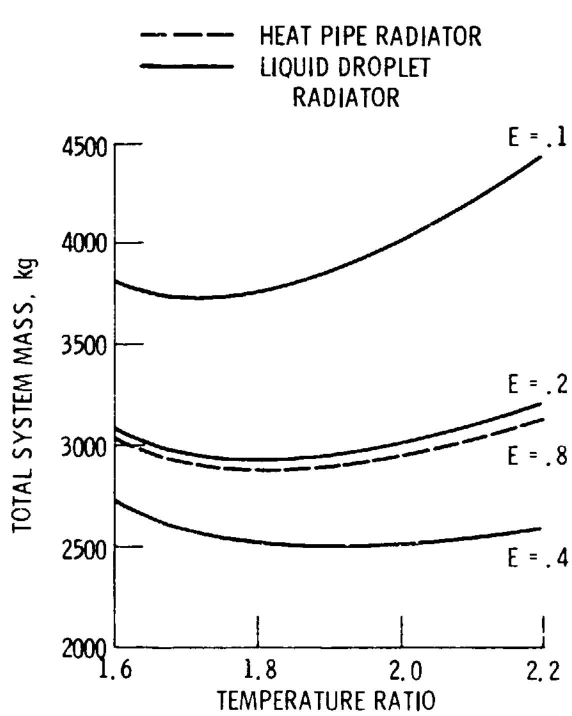

Figure 17. - Nuclear Stirling system mass comparisons for LDR and heat pipe radiator.

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16. Abstract

The NASA Lewis Research Center and the Air Force Rocket Propulsion Laboratory (AFRPL) are jointly engaged in a program for technical assessment of the Liquid Droplet Radiator (LDR) concept as an advanced high performance heat rejection component for future space missions. NASA Lewis has responsibility for the technology needed for the droplet generator, for working fluid qualification, and for investigating the physics of droplets in space; NASA Lewis is also conducting systems/mission analyses for potential LDR applications with candidate space power systems. For the droplet generator technology task, both micro-orifice fabrication techniques and droplet stream formation processes have been experimentally investigated. High quality micro-orifices (to 50 μm diameter) are routinely fabricated with automated equipment. Droplet formation studies have established operating boundaries for the generation of controlled and uniform droplet streams. A test rig is currently being installed for the experimental verification, under simulated space conditions, of droplet radiation heat transfer performance analyses and the determination of the effective radiative emissivity of multiple droplet streams. Initial testing has begun in the NASA Lewis Zero-Gravity Facility for investigating droplet stream behavior in microgravity conditions. This includes the effect of orifice wetting on jet dynamics and droplet formation. The mission analyses are identifying integration requirements for the LDR with solar and nuclear power systems. Results for both Brayton and Stirling power cycles have identified favorable mass and size comparisons of the LDR with conventional radiator concepts. The objective of the program tasks is to resolve critical technology issues which confront the development and design of a prototype LDR system for testing in space environment. An essential part of the current technical program pertains to the experimental investigation of multistream dynamics and thermal behavior for the droplet sheet mass in simulated space environment.

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