NASA TM-79132

NASA Technical Memorandum 79132

NASA-TM-79132 19790014255

TITANIUM-ALLOY, METALLIC-FLUID HEAT PIPES FOR SPACE SERVICE

James F. Morris
Lewis Research Center
Cleveland, Ohio

March 1979

1 Report No NASA TM-79132	2 Government Accession No	3 Recipient's Catalog No
4 Title and Subtitle TITANIUM-ALLOY, METALLIC-FLUID HEAT PIPES FOR SPACE SERVICE		5 Report Date March 1979
		6 Performing Organization Code
7 Author(s) James F. Morris		8 Performing Organization Report No E-9974
		10 Work Unit No
9 Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11 Contract or Grant No
		13 Type of Report and Period Covered Technical Memorandum
12 Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14 Sponsoring Agency Code
15 Supplementary Notes		

16 Abstract

Reactivities of titanium limit its long-term terrestrial use for unprotected heat-pipe envelopes to about 870 K (1100° F) But this external thermochemical limitation disappears when considerations shift to space applications In such hard-vacuum utilization much higher operating temperatures are possible. Primary restrictions in space environment result from vaporization, thermal creep, and internal compatibilities Unfortunately, a respected heat-pipe reference indicates that titanium is compatible only with cesium from the alkali-metal working-fluid family This problem and others are subjects of the present paper which advocates titanium-alloy, metallic-fluid heat pipes for long-lived, weight-effective space service between 500 and 1300 K (440° and 1880° F)

17 Key Words (Suggested by Author(s)) Heat pipes Titanium alloys Metallic fluids Space applications		18 Distribution Statement Unclassified - unlimited STAR Category 34	
19 Security Classif (of this report) Unclassified	20 Security Classif (of this page) Unclassified	21 No of Pages	22 Price*

* For sale by the National Technical Information Service Springfield Virginia 22161

E-9974

LIGHTWEIGHT HEAT PIPES FOR SPACE SERVICE AT INTERMEDIATE AND HIGH TEMPERATURES

Contemplate a heat pipe delivering 1000's of W/cm^2 at 1300 K (1880° F), 6700 N/m^2 ($\sim$1 psi) internal pressure, and 0 0003 cm/yr ($\sim$0.1 mil/yr) external losses in hard vacuum - with only half the weight of its molybdenum or niobium counterparts That capability represents the potentiality of the titanium-alloy, lithium heat pipe Furthermore, metallic-fluid, titanium-alloy heat pipes as a group promise weight-effective, high-performance space service from temperatures tolerating aluminum to those demanding refractory metals Between these material extremes stainless-steel and superalloy heat pipes span the gap currently with about twice the envelope, wick density of titanium

This space heat-pipe range gains importance in light of rapidly increasing "mission power requirements" (fig 1, ref 1) Anticipated space-power increases dictate "future trends toward higher energy density equipment . . , efficient transport of thermal energy . ; modularity to minimize cost, allow growth, and permit replacement or maintenance for long life; and basic life improvement through design and materials selection " These projections are emphatic points made by the Thermal Management Workshop of the Future Orbital Power Systems Technology Requirements symposium (Lewis Research Center, June 1978, ref. 1) That group also emphasized "needs for higher temperature heat acquisition and rejection."

In consonance with this mandate, titanium-alloy, metallic-fluid heat pipes offer potential heat-supply and -removal systems for space Brayton and thermoelectric power generators (refs 2 to 4) Such heat pipes should also allow substantial weight and size savings in the very large high-temperature radiators for multihundred-kilowatt space power generation like thermionic energy conversion for nuclear electric propulsion (refs 2 to 6) Additional applications comprise a variety of intermediate-temperature space radiators, leading-edge isothermalizers (with cladding if necessary) for entry vehicles, and solar-thermal collection as well as transmission. Also titanium alloy, lithium heat pipes will facilitate space processing like containerless melting, low-stress sintering, and single-crystal growing in the bulk from melts (GaSb, Ge, GeSe, GeTe, InSb, Sn, etc.) and as whiskers by vapor deposition

But for this range of weight-effective heat pipes, do other versions like the beryllium, lithium combination deserve consideration? Over and above the controversial fabrication and processing problems of beryllium its vapor pressure is about five orders of magnitude greater than that of titanium ($\sim 3\times10^{-4}$ cm/yr at 900 K for Be and at 1300 K for Ti). Furthermore the solubility of beryllium

N79-22426#

in lithium apparently reaches 1000's of ppm near 1000 K (refs 7 to 12). Reference 9 tabulates atomic-percent solubilities for beryllium at 600° C as ~0.2 in lithium, ~2 in sodium, ~0.1 in potassium, ~0 2 in rubidium, and ~0.2 in cesium. Of course, the lightweight elements magnesium and aluminum, melt at prohibitively low temperatures (~650° and ~660° C). And magnesium has a vapor pressure higher than that of lithium So on the basis of these simple eliminations titanium appears to be the best low-density structural metal to consider for metallic-fluid heat pipes in space applications.

Unfortunately a respected "heat-pipe design handbook" (ref 13) indicates that titanium is compatible with cesium (cites refs.) and incompatible with lithium, sodium, potassium, and mercury (cites no refs) This observation has impressed heat-pipe workers throughout the world (ref 14, for example).

However, non-heat-pipe publications contest this negative viewpoint And the present paper discusses these implications as well as other aspects of titanium-alloy, metallic-fluid heat pipes for long-lived, weight-effective space service between 500 and 1300 K

BACKGROUND OF TITANIUM-ALLOY, METALLIC-FLUID HEAT PIPES FOR SPACE

Titanium is an excellent prospect for space heat-pipe applications because of its unusual properties: "Titanium is as strong as steel, but 45 percent lighter It is 60 percent heavier than aluminum, but twice as strong" (ref 15) In fact titanium has a 4 5-g/cm^3 density compared with 8 to 10 g/cm^3 for stainless steels, superalloys, niobium, and molybdenum. It melts at 1941 K in contrast to aluminum at 933 K and nickel, cobalt, and iron at 1726, 1765, and 1812 K And as previously stated, titanium vaporizes approximately 3×10^{-4} cm/yr at 1300 K in vacuum. This rate is suitable for long-term use in space and is about two orders of magnitude lower than vaporization of nickel, cobalt, and iron at 1300 K in vacuum.

Thermophysically, titanium undergoes a solid-phase alteration at about 1160 K: Here rising temperatures change the closely packed-hexagonal "alpha" structure to the body-centered-cubic "beta" configuration However this transformation, like the α-to-γ transition for iron at 1180 K, causes no great difficulties (ref. 16) The titanium α-to-β phase-change temperature rises with aluminum additions and falls (even below room temperatures) with inclusions of molybdenum, iron, chromium, or vanadium: Commercially available pure (99 6 percent) titanium and Ti, 5Al, 2.5Sn are alpha alloys; Ti, 8Mo, 8V, 2Fe, 3Al is a beta alloy; and the most widely used Ti, 6Al, 4V is an "alpha-beta" alloy.

Such metals are supplied in sheet, strip, plate, bar, ingot, wire, and tubing forms and are fabricable as thin foils, complex forgings, and fine extrusions. The fabricability and cost of titanium alloys are comparable with those of austenitic stainless steels.

Generally, however, the thermochemical, activity of titanium weighs against its high-temperature applications: "Titanium has a strong affinity for the gases hydrogen, nitrogen, and oxygen" (ref 17). This reactivity restricts long-term terrestrial use of titanium for unprotected heat-pipe envelopes to about 870 K. But these thermochemical reactions pose no problems for titanium-alloy heat pipes in the hard-vacuum ambiance of space applications In fact, titanium reactivity is an advantage "where space manufacture and/or assembly may be required to obtain feasible subsystem costs," "allow growth, and permit replacement or maintenance for long life," which are "needs specific to very large systems" (ref 1)

Titanium looms as an outstanding material for processing, fabrication, assembly, and repair in space (ref. 18): Ease of levitation (containerless melting) and the hard-vacuum environment eliminate many of the terrestrial processing problems But because of its reactivity titanium also adapts readily to light-weight forceless machining and cutting utlizing concentrated solar radiation with low-level oxidant augmentation Of course lasers, electron beams, or other high-energy sources should serve well also. In any event a small, well-directed oxygen jet used in conjunction with an energetic beam enables titanium alloys to provide some fuel very effectively for their own cutting Then titanium welds well and allows excellent capillary brazing. The latter will be very important in space where gravity will not compete with surface-tension and capillary forces Incidentally existing braze processes for aluminum are poor compared with those for titanium, are not truly capillary in nature, and probably will not improve in space. And finally, as the previous discussion stated, titanium alloys offer space-oriented properties like high strengths, low weights, high melting points, and low vapor pressures

Thus titanium could be a near-optimum material for much space fabrication and processing. In particular the preceding fabrication advantages, available concentrated solar energy, ambient hard vacuum for processing, and simplicity of design could encourage space manufacture and repair of titanium-alloy heat pipes for "very large systems "

However, maintaining this bright outlook depends on dispelling the previously mentioned doubt of titanium, metallic-fluid compatibilities (ref 13) In that vein references 19 and 20 recommend titanium "for the containment of lithium" above 500° C because of "negligible solution attack and thermal gradient mass transfer "

Reference 21 presents results for "corrosion resistance to contaminated molten lithium at 315° and 480° C; "titanium showed no evidence of attack " Culminating such findings, references 22 and 23 reveal that the compatibility of titanium with lithium at 1200 K is comparable with that of molybdenum And molbydenum is often considered the most lithium-resistant metal, suitable for lithium heat pipes to over 1600 K (TZM)

References 23 and 24 also report the solubility of titanium in 1370 K rubidium (4 ppm) as only 40 percent that of molybdenum Reference 25 states that titanium solubility in 1341 K potassium is lower than the resolutions of optical-spectrographic and wet-chemical analytic methods - indeterminably less than 4 ppm And finally reference 26 records the solubility of titanium in mercury as 3 ppm at 473 K and 8 ppm at 573 K

Summarizing with the aid of another citation (ref 27) reference 12 states that the "the Group IVB metals (Ti, Zr, Hf) form no intermetallics with the alkali metals Li, Na, and K and are insoluble in them "

Apparently the probability for successful space applications of titanium-alloy, metallic-fluid heat pipes is relatively high

FUTURE OF TITANIUM-ALLOY, METALLIC-FLUID HEAT PIPES FOR SPACE

A condensed background for the decision to initiate an accelerated r and t project on titanium-alloy, metallic-fluid heat pipes for space appears in table I The 7000-W/cm^2 sonic limit given in that tabulation is apropos because the 1300 K example falls on the low-temperature leg of the lithium-heat-pipe performance envelope. And choking is the theoretic (relatively nonisothermal) operating restriction for low-pressure (low-temperature) heat pipes

In that vein, table II presents sonic limits and vapor pressures for relatively low-temperature alkali-metal heat pipes: For a given working fluid, heat-pipe applications often range from about 0 1 to 10 atmospheres Such a pressure rise for alkali metals corresponds to an increase of 340° to 460° C making considerations of chemical stability and envelope creep far more important But thermal power densities also grow. For example, a sodium heat pipe near 1220 K (~2 atm) transported over 1.5×10^8 W/m^2 axially (ref 28) That loading is approximately 40 percent of the applicable theoretic wicking limit and an order of magnitude higher than the 900 K sonic value of table II However, as tables I and II reveal, lithium also offers high performances in the 1200-to-1300 K range, but with very low internal pressures. So lithium would minimize creep in high-temperature titanium heat pipes for space applications.

Table II also implies that in suitable space heat-pipe configurations lithium might serve down to 1100 K; sodium, down to 800 K; potassium, to 700 K; cesium, 650 K; and mercury, 450 K. Approximate temperatures for 1-atmosphere heat-pipe operation are 630 K for mercury; 960 K for cesium; 1030 K, potassium; 1150 K, sodium; and 1600 K, lithium. Of course, the last temperature is considerably higher than the 1300 K recommended as the near-maximum for long-term space service of lithium, titanium heat pipes (<0.0003 cm/yr, <0 07 atm) At 1300 K, vapor pressures for sodium, potassium, and cesium are about 3 3, 7 2, and 10 atmospheres These numbers emphasize the need to optimize the physical effects of temperature, internal pressure, envelope creep strength, and wall thickness, in addition to the performance and compatibility characteristics Resulting weight optimizations for titanium-alloy, metallic-fluid heat pipes are very important space-application parameters This consideration becomes critical for the very large high-temperature radiators required by multihundred-kilowatt power systems.

Thus, preparing for space utilization of titanium-alloy, metallic-fluid heat pipes involves not only compatibility and performance verifications but also design calculations based on thermal-creep and vaporization data for commercially available titanium alloys at high temperatures. Unfortunately there is a paucity of this information because most titanium experience is terrestrial at temperatures below 870 K.

So to cover all such aspects the r and t project for titanium-alloy, metallic-fluid heat pipes must verify compatibilities and performances of lithium, sodium, potassium, cesium, and mercury with the basic alloy (99.6 percent pure titanium). Also near-1300 K tests with lithium should yield creep and vaporization data as well as accelerated-life and performance results for commercially available, but basically different titanium alloys: 99 6 percent-Ti alpha alloy; Ti, 8 Mo, 8V. 2Fe, 3Al beta alloy; and Ti, 6Al, 4V "alpha-beta" alloy Of course predictions of alloy-additive effects based on a simple-mixture model for the constituents are unreliable. This observation is particularly true because of intermetallic compounds formed by titanium-alloy components like aluminum with iron, molybdenum, titanium, or vanadium and like iron with molybdenum, titanium, or vanadium (refs 10 to 12)

Compatibility determination like performance verification requires evaluation in the heat-pipe mode for reasons described and diagrammed in figures 2(a) and (b). As figure 2(a) states, "capsule, coupon, or ordinary-flow methods do not approximate heat-pipe life testing But a suitable cylindric screen changes an ineffective capsule into a heat pipe - for effective, economical life testing." And of course the nearly isothermal heat pipe is one of the best specimens for the study of envelope vaporization and thermal creep as well as numerous other phenomena like adsorption, chemical reaction, thermal radiation, nuclear-reactor environmental effects, and thermionic emission.

References 29 and 30 detail sample-fabrication and multipurpose-test procedures for the previously mentioned r and t project on titanium-alloy, metallic-fluid heat pipes for space This work should result in a new group of intermediate- and high-temperature heat pipes for long-term, weight-effective, economical service in space applications

REFERENCES

1. Future Orbital Power Systems Technology Requirements NASA CP-2058, 1978.

2 Koenig, D R ; Ranken, W A.; and Salmi, E W : Heat Pipe Reactors for Space Power Applications J Energy, vol 1, July-Aug 1977, pp 237-243

3. English, R. E : Comment on "Heat-Pipe Reactors for Space Applications " J Energy, vol 2, May-June 1978, pp 191-192
Ranken, W A ; and Koenig, D R : Reply by Authors to R E English, ibid p. 192

4 English, R E : Alternative Power Generation Systems Future Orbital Power Systems Technology Requirements NASA CP-2058, 1978, pp 113-131

5 Morris, J F : High-Temperature, High-Power-Density Thermionic Energy Conversion for Space NASA TM X-73844, 1977

6 Morris, J F : Optimize Out-of-Core Thermionic Energy Conversion for Nuclear Electric Propulsion NASA TM-73892, 1977

7 Jesseman, D S ; et al : Preliminary Investigation of Metallic Elements in Molten Lithium. NEPA-1465, U S Atomic Energy Comm , 1950 (declass 1961)

8 Bychkov, Yu F.; Rozanov, A N ; and Yakovleva, V B : Determination of the Solubility of Metals in Lithium At Energ. (USSR), vol 7, no 6, 1959, pp. 531-536 Sov At Energy, vol 7, 1961, pp 987-992 (Translation)

9. Klemm, W ; and Kunze, D : Systems of Alkali and Alkaline Earth Metals. The Alkali Metals. The Chemical Society, London, 1967, pp 3-22

10. Elliott, R P., ed.: Constitution of Binary Alloys First Supplement McGraw-Hill Book Co., Inc., 1965

11. Shunk, F A., ed : Constitution of Binary Alloys Second Supplement McGraw-Hill Book Co., Inc , 1965

12 Moffatt, W G : Binary Phase Diagrams Handbook, General Electric Co , Schenectady, New York, 1976

13 Skrabek, E A ; et al : Heat Pipe Design Handbook (DTM-72-3-PT-1, Dynatherm Corp.; NASA Contract NAS9-11927) NASA CR-134264, 1972

14. Shchukin, V K ; et al.: Heat-Pipe Regenerator for Gas Turbine Engine Izv Vyssh Ucheb Zaved Aviats Tekh , vol 19, 1976, pp 172-175

15 Lynch, Charles T., ed : CRC Handbook of Materials Science Chemical Rubber Co Press Inc , 1974

16 Touloukian, Yeram S , ed : Thermophysical Properties of High Temperature Solid Materials MacMillan Co , 1967

17 Bardes, Bruce P , ed : Metals Handbook Ninth ed American Society for Metals, 1978

18. Adams, C. M : Space Production, Assembly, and High-Vacuum Fabrication Space Manufacturing Facilities: Space Colonies American Institute of Aeronautics and Astronautics, Inc , 1977, pp 99-103

19 Natesan, K : Interactions Between Structural Materials and Liquid Metals at Elevated Temperatures. Metall Trans , vol 6A, no 6, June 1975, pp 1143-1153

20 Cybulskis, P , ed : Liquid Metals MCIC Review of Metals Technol , June 4, 1975.

21 DeVries, G.: The Corrosion of Metals by Molten Lithium Corrosion by Liquid Metals, J E. Draley and J R Weeks, eds , Plenum Press, 1970, pp 251-269.

22. Leavenworth, H W ; and Cleary, R E : Solubility of Nickel, Chromium, Iron, Titanium and Molybdenum in Liquid Lithium Acta Met , vol 9, 1961, pp. 519-520

23 Mausteller, J W ; Tepper, F ; and Rodgers, S. J : Alkali Metal Handling and Systems Operating Techniques Gordon and Breach Sci Publ Inc., 1967.

24 Young, P F : Determination of Temperature Coefficient of Solubility of Various Metals in Rubidium. AGN-8063, Aerojet-General Nucleonics, 1962

25 Stecura, S.: Solubilities of Molybdenum, Tungsten, Vanadium, Titanium, and Zirconium in Liquid Potassium Corrosion by Liquid Metals, J E Draley and J. R Weeks, eds , Plenum Press, 1970, pp. 601-611

26. Jangg, G.; and Palman, H.: The Solubility of Various Metals in Mercury Z Metallk , vol. 54, 1963, pp 364-369

27 Weeks, J R : Liquidus Curves of Nineteen Delute Binary Alloys of Bismuth Trans. ASM, Quart., vol 58, no 3, 1965, pp 302-322

28. Vinz, P ; and Busse, C A.: Axial Heat Transfer Limits of Cylindrical Sodium Heat Pipes Between 25 W/cm^2 and 15 5 kW/cm^2 Presented at the International Heat Pipe Conference, Stuttgart, F R Germany, Oct 1973, paper 2-1.

29. Fabrication of Titanium, Metallic-Fluid Heat Pipes and Titanium-Alloy Metallic-Fluid Heat Pipes. Invitation For Bid 3-857216-B, NASA Lewis Research Center, Jan 8, 1979

30 Compatibility and Performance Studies of Titanium-Alloy, Metallic-Fluid Heat Pipes, Request For Proposal 3-855711-Q, NASA Lewis Research Center, Jan. 4, 1979

TABLE I. - TITANIUM-ALLOY, METALLIC-FLUID HEAT PIPES FOR 500 TO 1300 K SPACE APPLICATIONS

Needed because heavy heat pipes now serve between temperatures tolerating aluminum and those demanding refractory metals

- Heating and/or cooling: Brayton, thermoelectrics, Rankine
- Heat collection: nuclear reactors, solar concentrators, radioisotopes
- Cooling: thermionic converters, re-entry and hypersonic leading edges
- Space radiators: intermediate and high temperatures
- Space processing: Containerless melting; crystal growth (vapor or melt); property, transport, and reaction determination and control

Undeveloped because of erroneous compatibilities information

Promising because titanium is

- As strong as steel, which is 75 percent heavier
- Twice as strong as aluminum, which is 40 percent lighter
- As alkali-metal resistant as molybdenum, which is 120 percent heavier

Effective because, for example, a 1300 K titanium, lithium heat pipe offers

- $\sim$7000 W/cm^2 sonic limit - high performance
- $<$0.07 atm, internal pressure - little thermal creep
- $<$0 0003 cm/yr vaporization in space - long life
- $\sim$lithium compatibility of molybdenum-long life
- $<$half the weight of molybdenum - lightweight
- $\sim$cost and fabricability of austenitic stainless steel - economy

TABLE II - HEAT-PIPE SONIC LIMITS

[Each set of numbers → temperature: thermal-power density (vapor pressure) → ^{o}K: W/m^2 (N/m^2)*.]

Water	300: 9×10^{6} (2.5×10^{3})	400: 5×10^{8} (2.5×10^{4})	500. 3.6×10^{9} (2.6×10^{6})
Mercury	400: 1.4×10^{5} (1.5×10^{2})	500: 6×10^{6} (6×10^{3})	600: 6×10^{7} (6×10^{4})
Cesium	600: 6×10^{5} (5×10^{2})	700: 7×10^{6} (4×10^{3})	800: 3×10^{7} ($1\ 7\times10^{4}$)
Potassium	600: 3×10^{5} (8×10^{1})	700: 3.5×10^{6} (1×10^{3})	800: 2×10^{7} (6×10^{3})
Sodium	700: 5×10^{5} (1×10^{2})	800: 4.5×10^{6} (1×10^{3})	900: 2×10^{7} (5×10^{3})
Lithium	900: 1.5×10^{5} (1.3×10^{1})	1100: 6×10^{6} ($5\ 6\times10^{2}$)	1300: 7×10^{7} (6.7×10^{3})

*Multiply N/m^2 by $\sim10^{-5}$ for atm

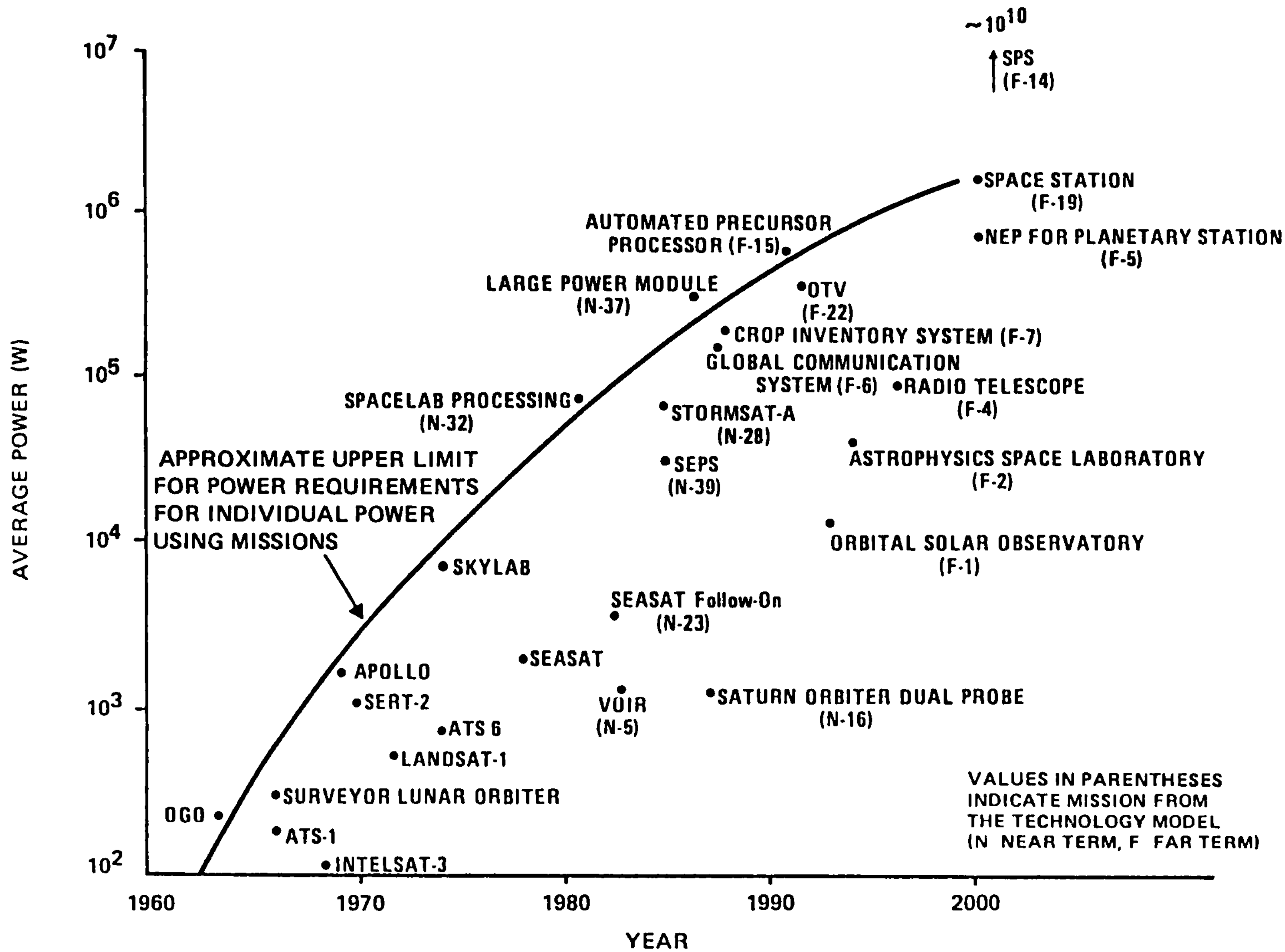
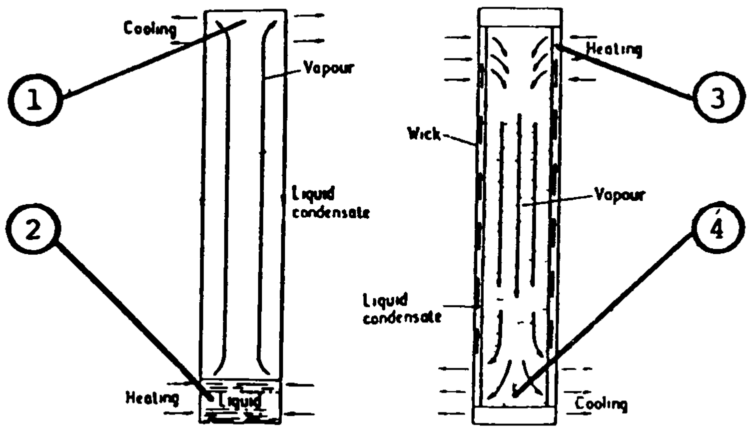


Figure 1 . Mission Power Requirements

HEAT-PIPE MATERIALS COMPATIBILITY: LIFE TESTING



REFLUX CAPSULE HEAT PIPE

REFLUX-CAPSULE TEST FLUIDS

(1) VAPORIZE, SWEEP NONCONDENSIBLE CORROSION PRODUCTS TO CAPSULE TOPS, CONDENSE,

(2) FORM, DISSOLVE, AND DRAIN NONVOLATILE CORROSION PRODUCTS TO CAPSULE BOTTOMS, DILUTING NONVOLATILE CORROSION PRODUCTS IN TEST-LIQUID POOLS.

HEAT-PIPE WORKING FLUIDS,

(3) IN CONTRAST, TRANSPORT DISSOLVED CORROSION PRODUCTS THROUGH WICK ARTERIES TO EVAPORATORS, MOVE TO EVAPORATING SURFACES THROUGH WICK CAPILLARIES, VAPORIZE, LEAVING CONTINUOUSLY CONCENTRATING NONVOLATILE CORROSION PRODUCTS IN EVAPORATOR WICKS,

(4) THEN SWEEP NONCONDENSIBLE CORROSION PRODUCTS TO CONDENSER ENDS, LIQUEFY, AND RECYCLE.

CAPSULE, COUPON, OR ORDINARY-FLOW METHODS DO NOT APPROXIMATE HEAT-PIPE LIFE TESTING.

BUT A SUITABLE CYLINDRIC SCREEN CHANGES AN INEFFECTIVE CAPSULE INTO A HEAT PIPE-FOR EFFECTIVE, ECONOMICAL LIFE TESTING.

FIGURE 2A

HEAT-PIPE MATERIALS COMPATIBILITY: LIFE TESTING

WORKING VAPOR

RECEIVES ENTHAPY OF VAPORIZATION FROM HEAT SOURCE,
FLOWS FROM EVAPORATOR THROUGH ADIABATIC SECTION,
SWEEPS ANY NONCONDENSIBLE CORROSION PRODUCTS TO CONDENSER END,
LIQUEFIES, GIVING UP ENTHALPY OF CONDENSATION TO HEAT RECEIVER.

WORKING LIQUID

CONTACTS ALL WICK AND WALL SURFACES,
CORRODES AND DISSOLVES SOLIDS TO SOME EXTENT,
ATTACKS MORE READILY WITH SOME IMPURITIES PRESENT,
ATTACKS LESS READILY WITH GETTERING AND PASSIVATING ADDITIVES,
TRANSPORTS DISSOLVED CORROSION PRODUCTS THROUGH WICK ARTERIES,
LOCALIZES CORROSION PRODUCTS IN EVAPORATOR-WICK END,
MOVES TO EVAPORATING SURFACE THROUGH WICK CAPILLARIES,
VAPORIZES LEAVING NONVOLATILE CORROSION PRODUCTS BEHIND,
INTERACTS WITH THESE CONTINUOUSLY CONCENTRATING CORROSION PRODUCTS IN THE EVAPORATOR TO CORRODE FINE WICK STRUCTURES ADJACENT WALLS, END CAPS, AND CLOSURE WELDS.

HEAT-PIPE LIFE TESTING IS NOT APPROXIMATED BY CAPSULE, COUPON, OR ORDINARY-FLOW METHODS.

BUT A SUITABLE CYLINDRIC SCREEN CHANGES A CAPSULE INTO A HEAT PIPE FOR EFFECTIVE, ECONOMICAL LIFE TESTING.

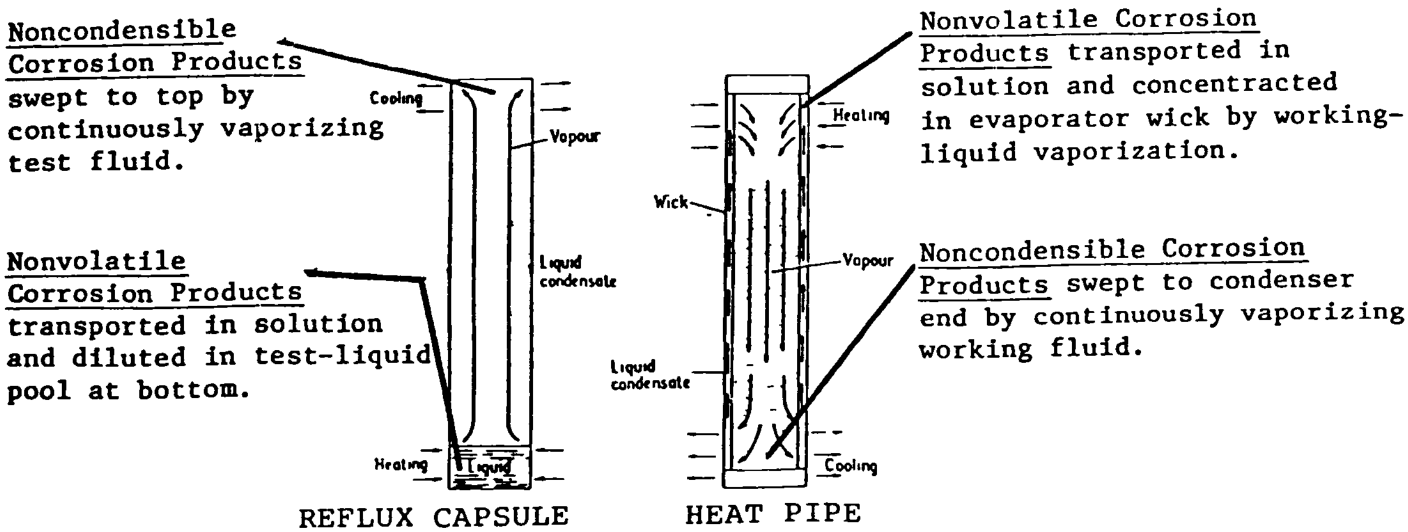


FIGURE 2B

End of Document