A Direct-Interface, Fusible Heat Sink for Astronaut Cooling

Curtis Lomax and B. W. Webbon

May 1990

N90-25292

(NASA-TM-102835) A DIRECT-INTERFACE,
FUSIBLE HEAT SINK FOR ASTRONAUT COOLING
(NASA) 15 p
CSCL 20D

Unclas
33/34 0291105

NASA
National Aeronautics and
Space Administration

NASA Technical Memorandum 102835
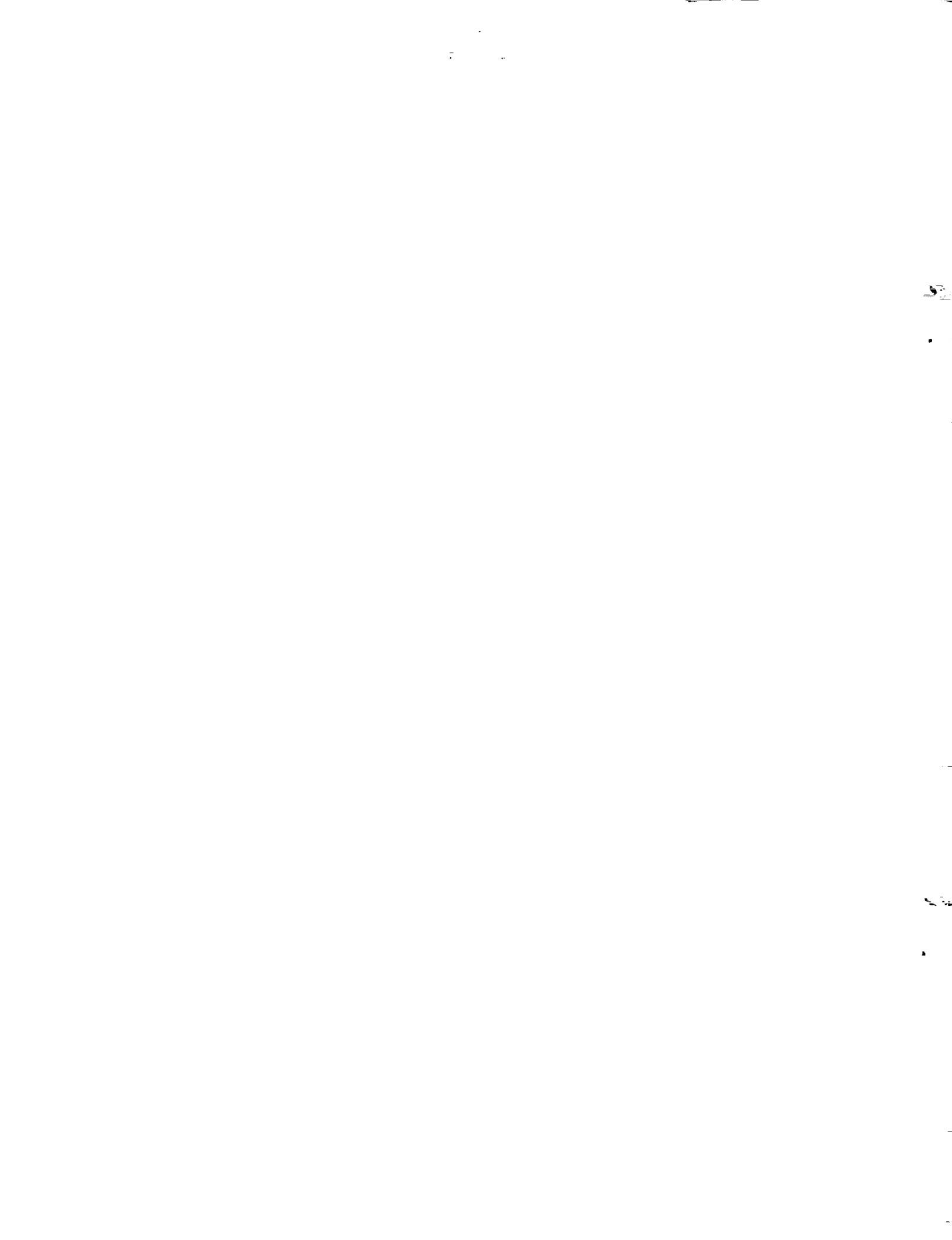
A Direct-Interface, Fusible Heat Sink for Astronaut Cooling

Curtis Lomax and B. W. Webbon
Ames Research Center, Moffett Field, California

May 1990

ABSTRACT

Astronaut cooling during extravehicular activity is a critical design issue in developing a portable life support system that meets the requirements of a space station mission. Some of the requirements are that the cooling device be easily regenerable and nonventing during operation. In response to this, a direct-interface, fusible heat sink prototype with freezable quick-disconnects has been developed. A proof-of-concept prototype has been constructed and tested that consists of an elastic container filled with normal tap water and having two quick-disconnects embedded in a wall. These quick-disconnects are designed so that they may be frozen with the ice and yet still be joined to the cooling system, allowing an immediate flow path. The inherent difficulties in a direct-interface heat sink have been overcome, i.e., (1) establishing an initial flow path, (2) avoiding low-flow freeze-up, and (3) achieving adequate heat-transfer rates at the end of the melting process. The requirements, design, fabrication, and testing are discussed.

INTRODUCTION

During extravehicular activity (EVA) a crew member generates metabolic energy, while portable life support systems (PLSS) and equipment produce additional heat. Ninety percent of metabolic energy is in the form of waste heat (1)[*] that must be removed from the body during the EVA to allow crew comfort and performance. Once removed from the body, the heat may be either stored or rejected, or both. On orbit, heat rejection occurs only by radiation or mass transfer. Heat storage may be accomplished by inducing a phase change in a substance or by causing an endothermic reaction to take place. Any self-contained system that attempts to control the thermal condition of an astronaut wearing a space suit will be limited by either capacity or rate of heat transfer. For example, a storage system will be limited by capacity, as will a mass transfer system. A radiation system will be limited by heat-transfer rate.

Thermal regulation of astronauts during EVA has been studied in some detail. In the past, cooling of space-suited crew members has been accomplished by use of a sublimator or an umbilical coolant supply. These systems provide adequate capacity and rate and are compact and lightweight. Their disadvantages are the venting and subsequent loss of water during operation or awkward umbilicals to manage. Future PLSS will require thermal regulatory systems that are nonventing, regenerable, and self-contained.

A nonventing, regenerable, and self-contained thermal regulatory proof-of-concept prototype has been developed. The prototype uses the solid-to-liquid phase-change properties of water to store waste heat. The device is a direct-interface, fusible heat sink. This paper discusses the requirements, design, fabrication, and testing of $\bar{c}$ 1/3-capacity, proof-of-concept prototype.

REQUIREMENTS

Future exploration missions will require an EVA system that can provide routine, possibly daily, operation that continues for months without support or resupply from surface-based resources or facilities. For these reasons, the thermal regulation system must be easily regenerable, nonventing, and extremely reliable. Some specific requirements are that the total capacity be 11 680 Btu (3420 W-hr) for an 8-hr EVA and that the device be able to cool at

---

[*]Numbers in parentheses designate references at end of paper.

2000 Btu/hr (585.6 W) for 15 min any time during this 8-hr period (5). More specific requirements are detailed in Table 1. The current proof-of-concept prototype is a 1/3 model (4000-Btu) (1171 W-hr).

DESIGN

There have been numerous astronaut cooling devices that use fusible heat sinks (2,3,4) However, none demonstrated a direct interface between the cooling liquid transport loop and the phase-change material; all of the previous designs have incorporated heat exchangers. This new design eliminates the use of a heat exchanger and allows direct-contact, forced-convection heat transfer between the cooling fluid and the phase change material. The benefits of this are reduced hardware weight, thermal resistance, and system complexity. The critical points of this design are the initial coolant flow path and adequate heat-transfer rate during the end of the melting process, as well as the design of quick-disconnects that seal to preclude microgravity fluid management problems.

If the requirement for cooling is 11680 Btu (3420 W-hr) per EVA (5), and if ice cooled to 0 °F (−17.8°C) and melt water warmed to 40 °F (4.4°C) is used as a phase change material, then approximately 70 lb (31.7 kg) of water must be included in the full-capacity device. This corresponds to 1.12 ft^3 (.032 m^3) for water or 1.25 ft^3. (.035 m^3) for ice. Conservatively estimating 30 lb (13.6 kg) for hardware, this gives a total weight of 100 lb (45.3 kg) for this thermal regulatory system.

The design consists of an elastic bladder cast from a two-part polyurethane elastomer that contains the water and ice and that is penetrated by two female connectors. The bladder is filled with water until it is in slight tension. Upon freezing, the bladder is stretched slightly owing to the expansion of the ice. When the first water is pumped into the bladder, the flexible wall is separated from the ice, stretching the bladder even more. Figure 1 illustrates this process. As the ice melts, the bladder relaxes and when the pump stops, at the end of the EVA, the bladder is again under slight tension. The container may be disconnected and refrozen at this point and the process repeated.

The initial coolant flow path is created by use of specially designed, freezable quick-disconnects (patent applied for) that allow the heat sink to be connected into the cooling loop and provide for a flow path. There are two identical connectors, each with a male and female portion. The two female portions of the connectors are embedded in the

elastic wall of the heat sink and frozen with it. Following regeneration of the ice container in a separate freezer, the male portions are inserted into the female halves and the flow is initiated. The water flows through the first male portion and into the empty cavity of the first female portion. Since the path is blocked by ice, the water then returns through an annular passage in the first male portion and travels through an external line to the second male portion. Upon exiting the second male portion, the water continues the circuit through the pump and liquid-cooled ventilation garment (LCVG) worn by the astronaut and returns to the first male portion. The warm water quickly melts the ice in the female half of the connector. Once the ice around the female portions has melted, the external bypass line is closed and all flow passes between the ice and the elastic bladder from inlet to outlet. Figures 2-4 show the mechanical aspects of the connectors.

The metabolic heat load will vary during the entire EVA, as will the potential heat-sink transfer rate. The latter is due to the changing surface area of the ice that the warm water encounters during the melt. The sink heat-transfer rate is controlled by adjusting the mass flow rate though the heat sink by a diverter valve. During low metabolic heat load conditions, only a small percentage of the 240 lb/hr (108.7 kg/hr) mass flow is diverted through the heat sink. During high metabolic heat load, a larger percentage is diverted. If, for example, a constant metabolic heat load is assumed throughout the melt, the mass flow rate through the heat sink must gradually increase as the melt progresses in order to maintain the heat-transfer rate. It is necessary that the device be designed such that adequate mixing occurs during the later stages of the melt in order to maintain proper heat-transfer rates and to fully utilize the phase change material.

FABRICATION

A test article was constructed to verify that the direct-interface, fusible heat sink concept was viable. The test article was arbitrarily chosen to be approximately 1/3 capacity, that is, it contained 1/3 the mass a system would need for a theoretical 8-hr EVA. Approximately 23 lb (10.4 kg) of water were used and the total heat capacity was 3841 Btu (1125 W-hr).

The construction of the experimental elastic bladder consists of two parts, a lid and a bucket that are held together by a metal clamp. The bucket and lids were made in two-part molds using a polyurethane elastomer. The clamp was machined from

2

Aluminium 6061-T6 and anodized black. Details of the assembly are presented in Figure 5.

Modifications were made to the test article as tests progressed. Three different lids were made, each lid with a different characteristic that testing indicated could be a possible improvement. Of the three lids, one accepted Tygon tubing without connectors, one accepted connectors, and one accepted connectors and included a baffle inside the bucket. The baffle was fixed to the undersurface of the lid and extended down to within 0.25 in. of the bottom of the bucket.

The connectors were made from a combination of Teflon-impregnated Delrin, O-rings, and stainless steel springs. All design and manufacturing were done in-house at NASA Ames Research Center .

TESTING

The prototype was frozen in a common household freezer, a process that took approximately 36 hr to complete. The prototype was suspended in a wood and fiberglass rack, allowing heat transfer only by free convection and radiation. Use of forced convection or conduction could increase the heat transfer rate from 10 to 100 times, thus decreasing the time to freeze significantly (6). (A future device will attempt to demonstrate reduced freeze time.) Upon extraction from the freezer, the unit was connected to the test apparatus and the pump was turned on. The test apparatus consisted of a variable-speed gear pump (Micropump model No. 120-306), a flow meter (Hedland Ram Flow sensor 645-002 and Signal conditioner 520-100), a regulator valve (Whitey SS-7RS8), T-type thermocouples, an HX-50 heat source made by Neslab Inc., Tygon tubing B-44-4X, and assorted Swagelog fittings. The thermocouple and flow data were collected via a data-acquisition peripheral (IDAC 3000 and Macontrol software) and subsequent calculations were performed on a Macintosh II using the spreadsheet Excel. This equipment was assembled such that, once the heat sink was plumbed in, one could control the flow and temperature into it . Figure 6 diagrams the test apparatus. The thermocouples monitored inlet and outlet temperature and the flow meter registered inlet flow.

Testing criteria consisted of two items. The primary criterion was that the device must be operable. That is, that one must be able to freeze the device, connect it into the coolant loop, and establish a flow path. The secondary criterion was that the heat-transfer rate be adequate until all the ice was melted. The first criterion could be judged by observation and the second by measurement of three parame-

ters: (1) flow rate through the heat sink, (2) inlet temperature, and (3) outlet temperature. These measurements can be used to calculate the heat-transfer rate into the heat sink. The heat-transfer rate determinations were only approximations during these proof-of-concept tests because the prototype was not insulated.

The test procedure was as follows.
1. Freeze the container.
2. Turn on the Neslab heat source and set temperature.
3. Connect the container into the coolant loop.
4. Initiate coolant flow through the container, 240 lb/hr (109 kg/hr), while measuring the parameters described above, and leave the device undisturbed throughout the melt. Observation of the melt process is important to determine the time it takes to completely melt the ice. Realistically, the device would be disturbed during normal use, but an undisturbed device was thought to provide a worst-case condition, since any motion would increase the heat-transfer rate. This procedure was followed for each of the configurations described below.

Four different configurations of the article were tested with numerous repetitions of each. The four configurations (Table 2) consisted of using the three lids at laminar inlet flow conditions for the first three tests and using the one lid that accommodated connectors at turbulent flow conditions for the fourth test. Each configuration was tested to determine the maximum heat-transfer rate possible for the given configuration.

DISCUSSION

The first test article (no connectors) was filled with tap water and cooled to approximately 4°F (−15.6°C). This article did not have connectors; it could accept 5/8-in. (15.9-mm) Tygon tubing after freezing. Upon connection of the Tygon tubing, the flow was initiated. The water proceeded to flow from inlet to outlet, forcing its way between the ice and the elastic bladder. This was confirmation that the concept of forming the initial flow path in a direct-interface fusible heat sink was possible and practical. Figure 7 shows the heat-transfer profile for this experiment. The heat-transfer rate dropped below 2000 Btu/hr (585.6 W) before all the ice was melted, presumably owing to channeling of the flow around the ice block. In subsequent tests, it was evident that the low heat-transfer rate was due to channeling because shaking of the device increased the heat-transfer rate significantly. It should be noted that all these tests were conducted in a 1-g environment

3

and that microgravity conditions could change the performance of these prototypes. A reduction in buoyant forces would be expected to preclude the formation of density gradients that inhibit mixing. Therefore, the devices performance in microgravity during melting is expected to be improved over the 1-g case. Therefore, design alternatives that would increase the quality of mixing and, consequently, the heat-transfer rate were investigated. The alternatives sought were those that would provide mixing without added power, complexity, or reduction in reliability.

The second test article (connectors/no baffles) did incorporate quick-disconnects but no baffles and it too had successful flow initialization. The inlet velocity was low and the inlet flow was laminar. Figure 8 shows the heat-transfer profile for this test. The minimum heat-transfer rate, 2000 Btu/hr (585.6 W) could not be maintained throughout the melt. Unlike the first configuration, the connectors directed the flow parallel to the lid. This flow direction increased channeling, resulting in a decrease in the heat-transfer rate. It is important to note that the ice was held down by the connectors as they protruded downward from the top of the container. The ice melted from the top down and once there was a large enough cavity to allow laminar flow (see Fig. 9) between inlet and outlet, the heat-transfer rate dropped dramatically, as shown in Figure 8. The heat-transfer profile in Figure 8 shows an increase in the heat-transfer rate at the end of the melt; this is due to the ice breaking loose from the connectors and floating up to the surface where it was in the flow path of the warmer water.

The third test article (connector / baffles) also had successful flow initiation. The heat-transfer rate profile was similar to that of the second prototype. The baffle seemed to have little if any effect on the heat-transfer rate. Again, the rise in heat-transfer rate at the end of the melt, as seen in Figure 10, is due to the ice breaking away from the connectors and floating to the surface.

All of the above configurations were successful in terms of initial coolant flow path, but were inadequate in terms of heat-transfer rate profiles. It was apparent that insufficient mixing inside the ice container was the cause, and another approach was investigated. The quick-disconnects were adjusted to increase the velocity at the inlet and thus provide a jetting action that would increase turbulence. The fourth configuration is identical to the three previous configurations except for inlet velocity and lack of baffles.

The fourth configuration was identical to the second, but the inlet velocity was increased, while the mass flow rate was maintained. Examination of Figure 11 shows the heat-transfer rate profile to be changed substantially. The heat-transfer rate was maintained above the minimum of 2000 Btu/hr (585.6 W) until and after all the ice was melted. Again, the test conditions sought to transfer heat into the ice as quickly as possible, and the charts represent the highest rates attainable for each configuration. This configuration was successful in both test criteria.

CONCLUSIONS

A direct-interface fusible heat sink has been constructed and tested. It performed adequately when judged by two criteria: (1) a heat-transfer rate during any time of the melt greater than 2000 Btu/hr (585.6 W) and (2) provision of a flow path during start-up operations. A flight-quality heat sink would probably weigh less than 100 lb (45.3 kg). The system is a viable method of thermal regulation and should be developed further for use during Space Station Freedom and exploration mission EVA. A full-scale working prototype that will be used in neutral buoyancy evaluations of space suits is planned.

REFERENCES

(1) J. L. Williams, B. W. Webbon, R. L. Copeland, Advanced Extravehicular Protective Study, Detailed Technical Notes. Unpublished.

(2) G. J. Roebelen, Jr., Fusible Heat Sink for EVA Thermal Control. Hamilton Standard. Tasks 1-5, May 1978.

(3) B. W. Webbon, Concept Evaluation Test of a Fusible Evaporative Astronaut Heat Sink, VMSC Report 00.1452, Voight Missiles and Space Co. July 1971.

(4) G. J. Roebelen, Jr. Ice Pack Heat Sink Subsystem - Phase I, Hamilton Standard Aircraft Corp, Windsor Locks, Connecticut June 1973. NASA CR-114624, SVHSER 6223.

(5) G. J. Roebelen, K. J. Dresser, E. W. Hodgson, and Chin Lin, RNT Control Subsystem for Extravehicular Activity, Hamilton Standard Div. of United Technologies Corp., Windsor Locks, Connecticut, SAE paper, Thirteenth Intersociety Conference on Environmental Systems, July 1983.

6) Holman, J. P., Heat-transfer, 6th ed. McGraw-Hill Book Co. New York. 1986.

Table 1. Design and Performance Requirements

EVA duration	8hr (5)
EVA environment	LEO (any orientation)
Environment load	0 Btu/hr (0 W) (5)
Metabolic heat load	
Minimum	400 Btu/hr (117 W)
Average	1000 Btu/hr (293 W)
Maximum	2000 Btu/hr (586 W) (5)
PLSS heat load	Average, 635 Btu/hr (186 W)
Net Heat Load	
Minimum	635 Btu/hr (186 W)
8-hr average	1500 Btu/hr (439 W)
15-min max	2000 Btu/hr 586 W) (5)
Total heat capacity	11680 Btu (3420 W) (5)
Cooling garment temperatures	
Minimum	60°F (15.5°C) (5)
Maximum	85°F (29.4°C)
Heat-sink outlet temperature	<40°F (4.4°C) (humidity control)
Regeneration time	Less than 16 hr
EVA frequency	8 hr/day, 6 day/Wk
Mission duration	6 mo
Operational lifetime	>1228 hr

Table 2. Prototype and Test Conditions

Config.	Connector	Inlet velocity	Baffles
First	No	Low	No
Second	Yes	Low	No
Third	Yes	Low	Yes
Fourth	Yes	High	No
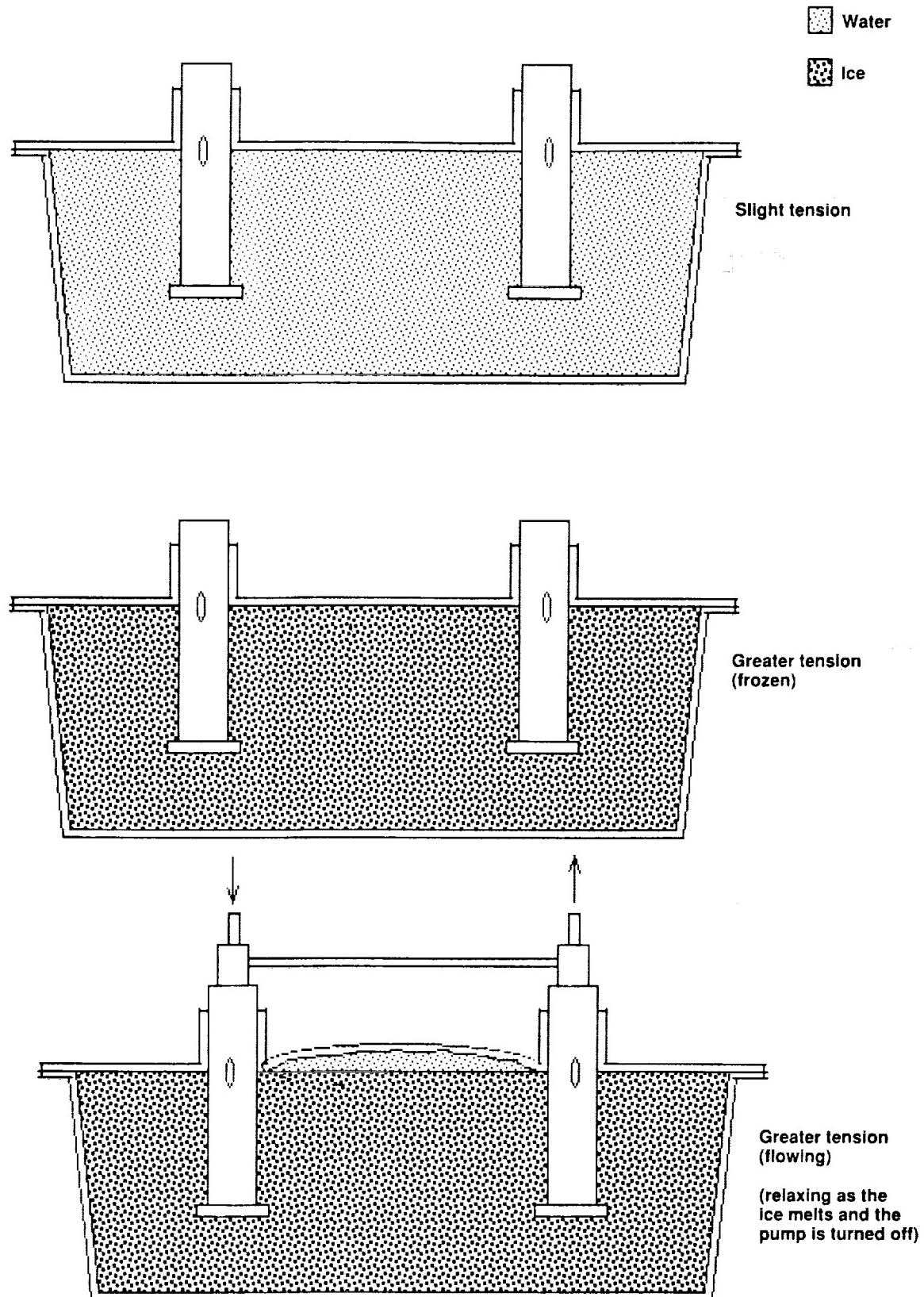
Figure 1. Diagram of regeneration and start-up of the direct-interface, fusible heat sink.

Inlet for first connector
Outlet for second connector

External line to second connector

Water

Ice

Male half

Air

Wall of plastic container

Ice

Frozen female half
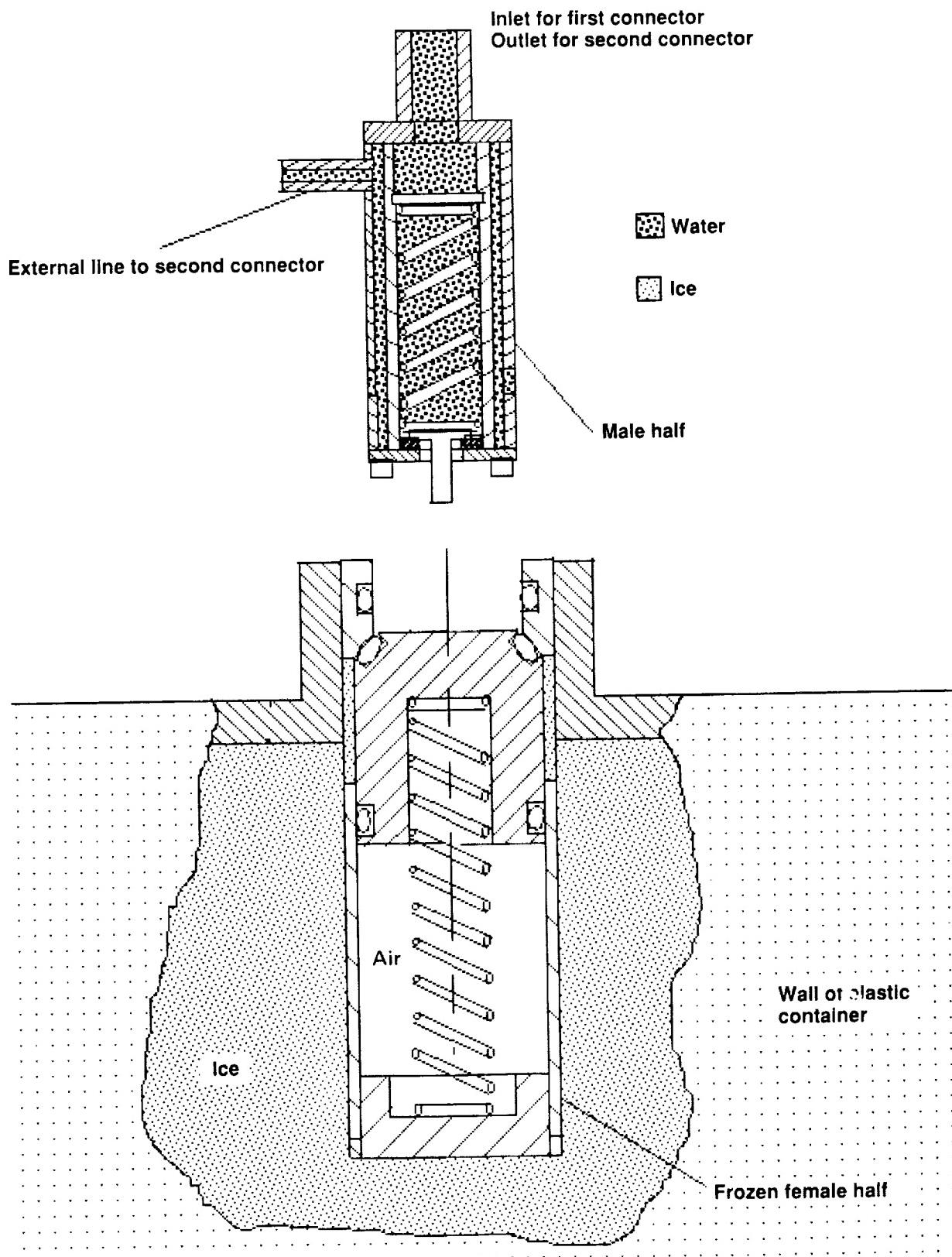
Figure 2. Unconnected frozen conditions for first or second connector, no flow possible.

7

Flow

Water

Ice

External line to second connector (open)

Flow

Male half

Path blocked by ice

Wall of elastic container

Air

Ice

Female half
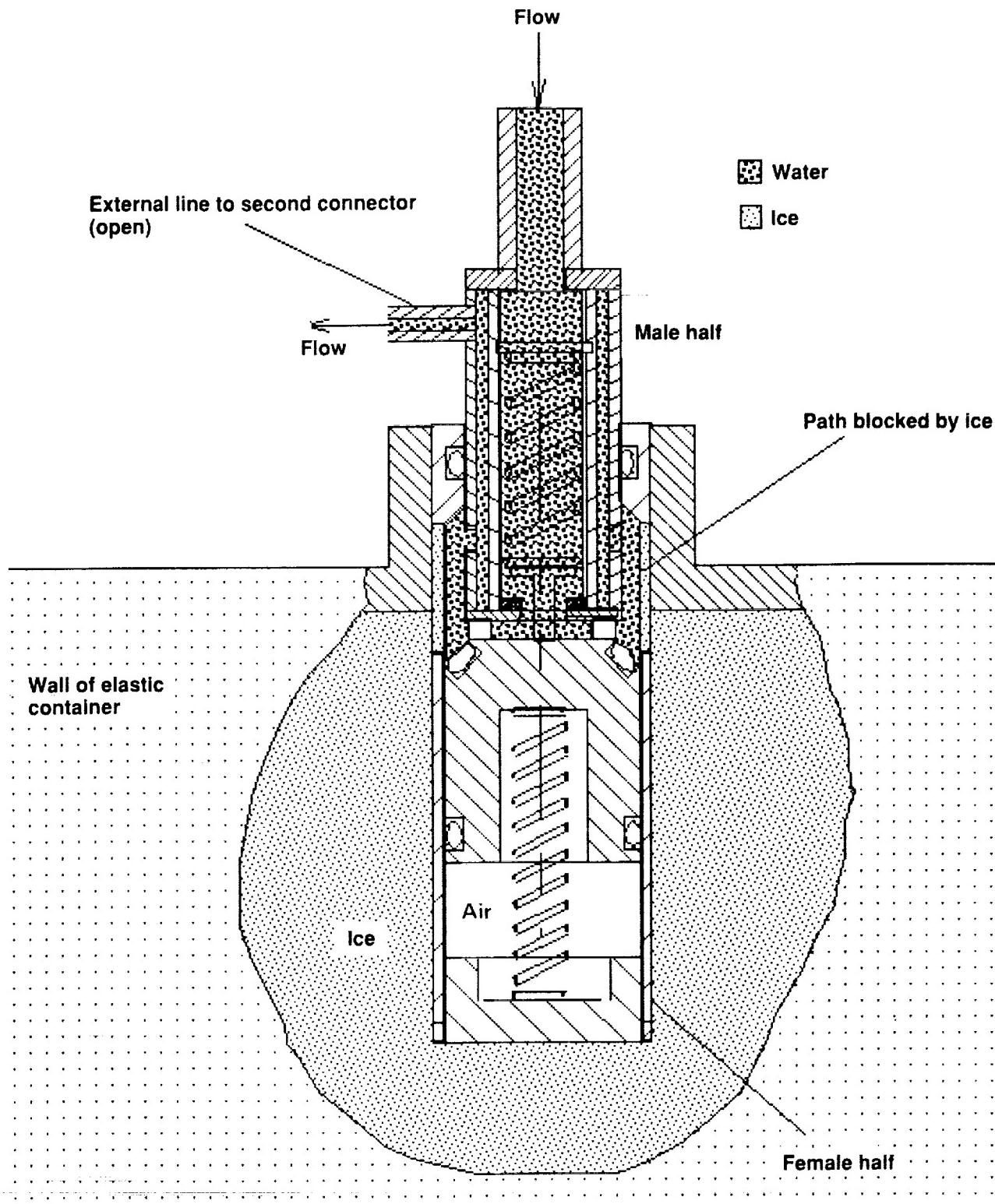
Figure 3. First connector (inlet), frozen condition, external flow possible (flow is reversed for second (outlet) connector).

Flow

Water

Ice

External line to second connector
(closed)

Male half

Wall of elastic
container

Flow

Air

Ice

Female half
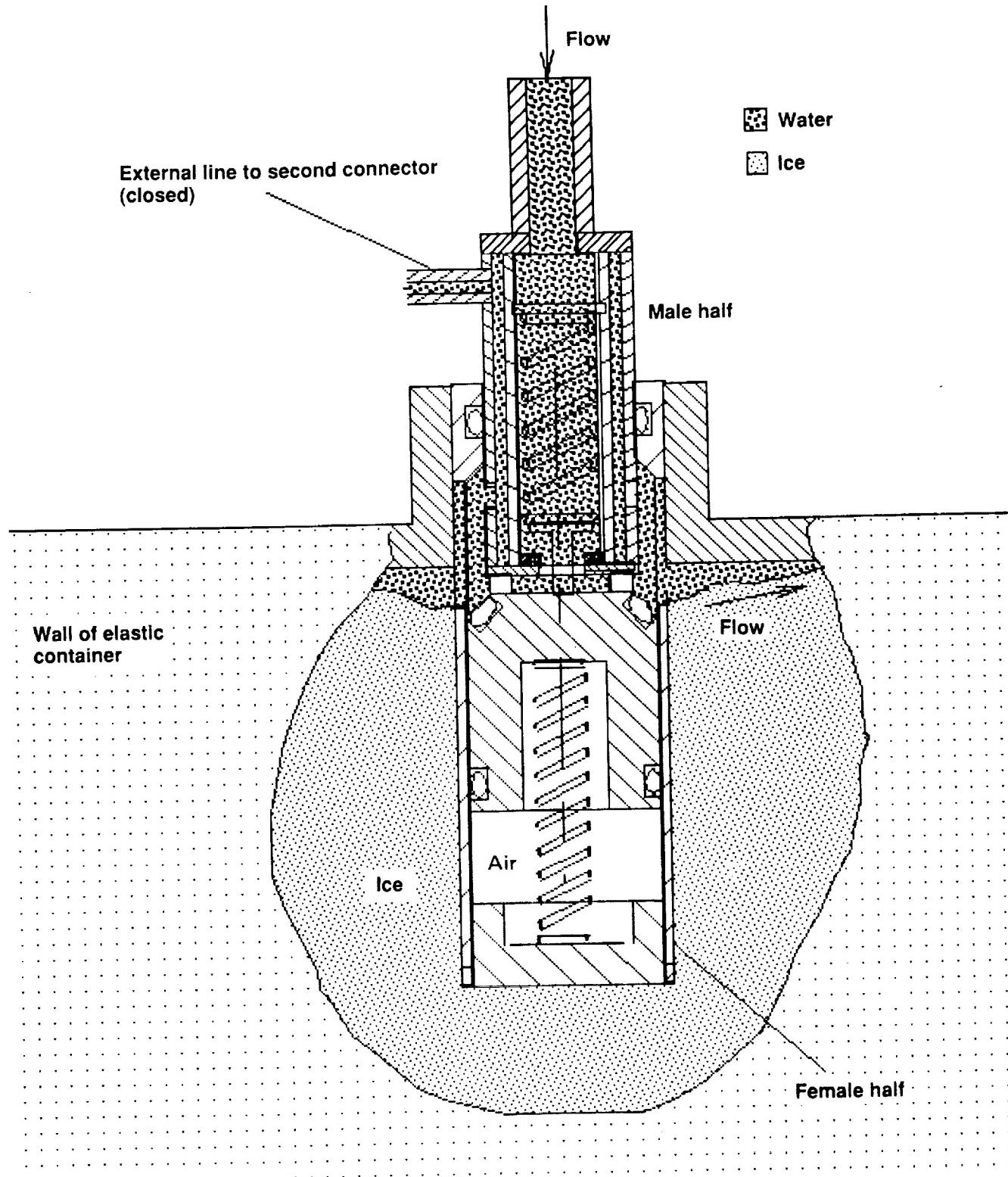
Figure 4. First connector (inlet), initial flow condition, internal flow is possible (flow is reversed for second (outlet) connector).
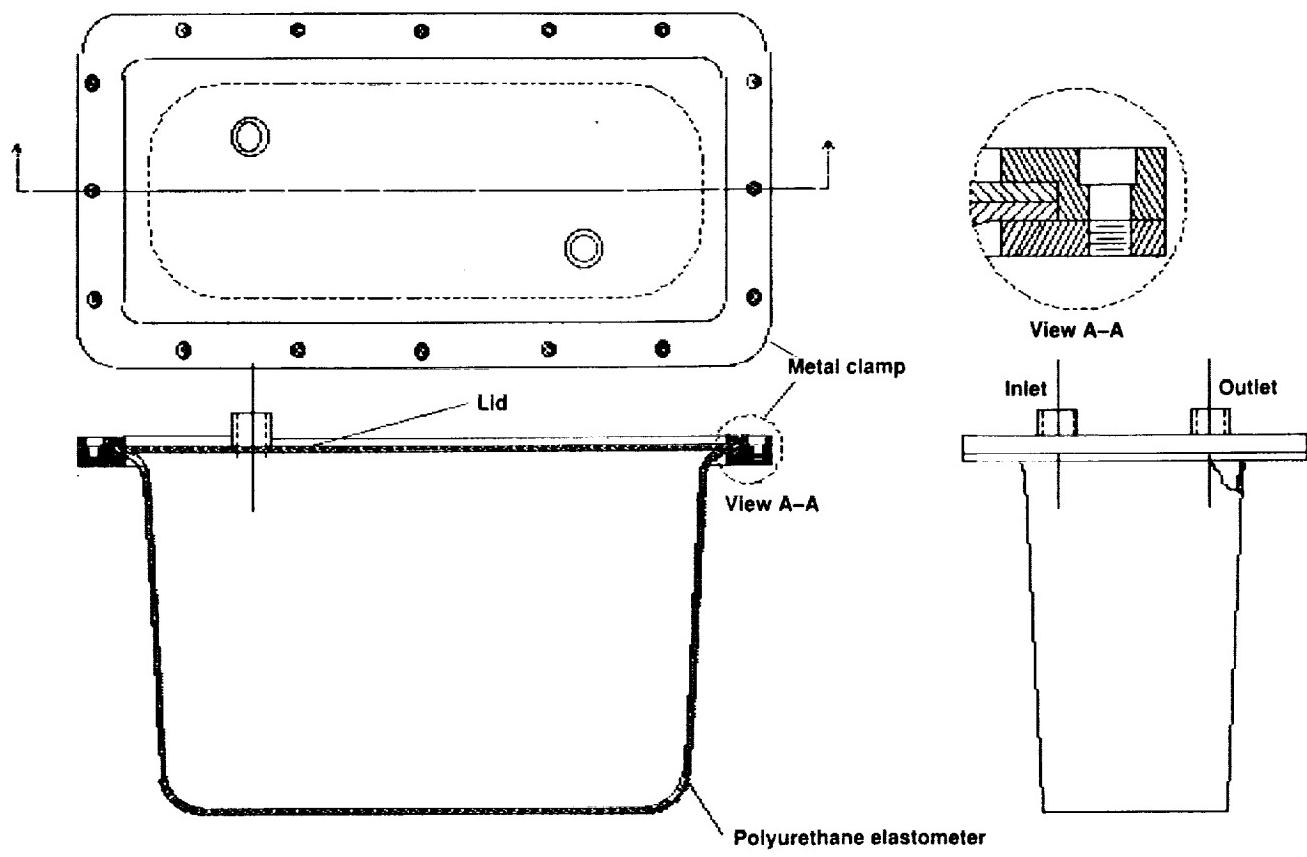
Figure 5. Details of direct-interface, fusible heat sink without connectors.
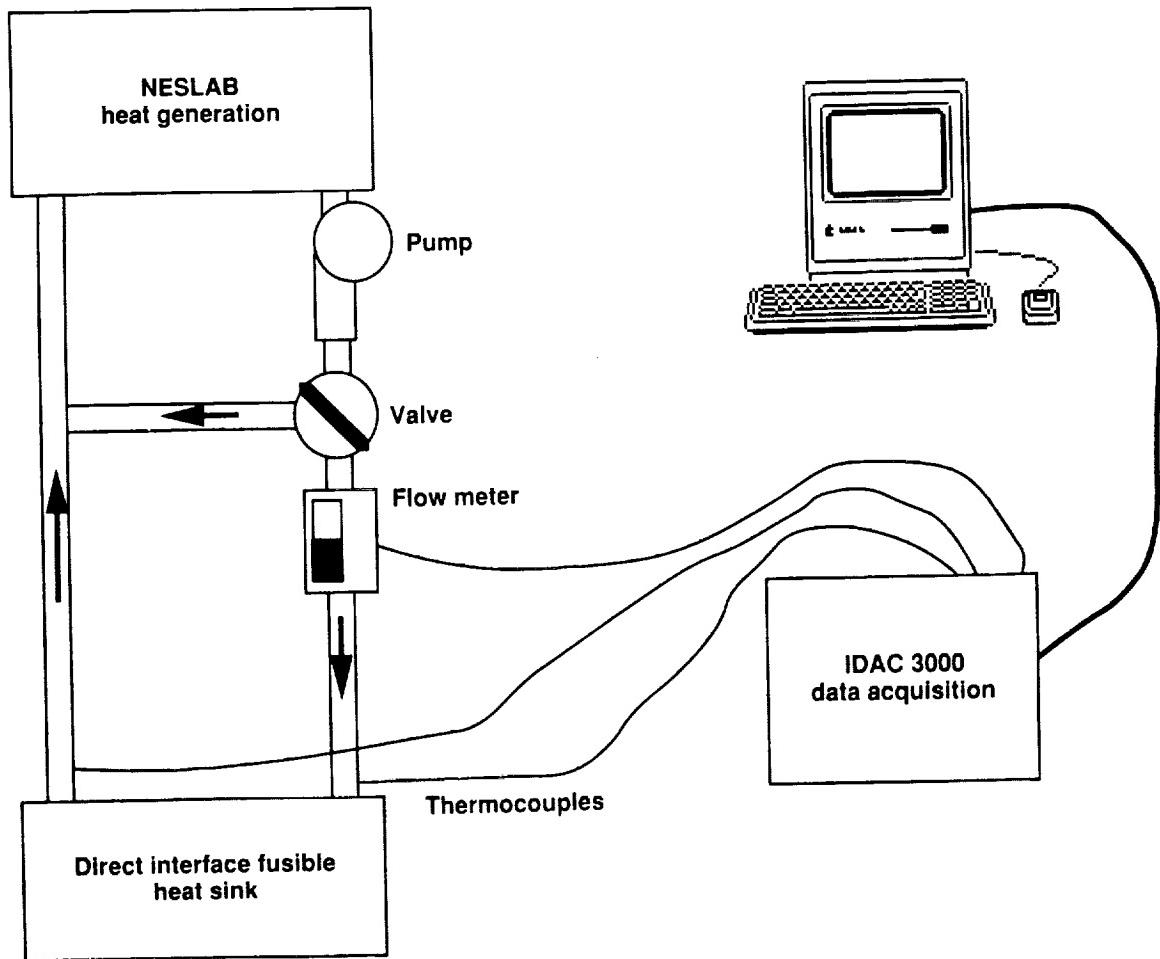
Figure 6. Schematic of test setup.
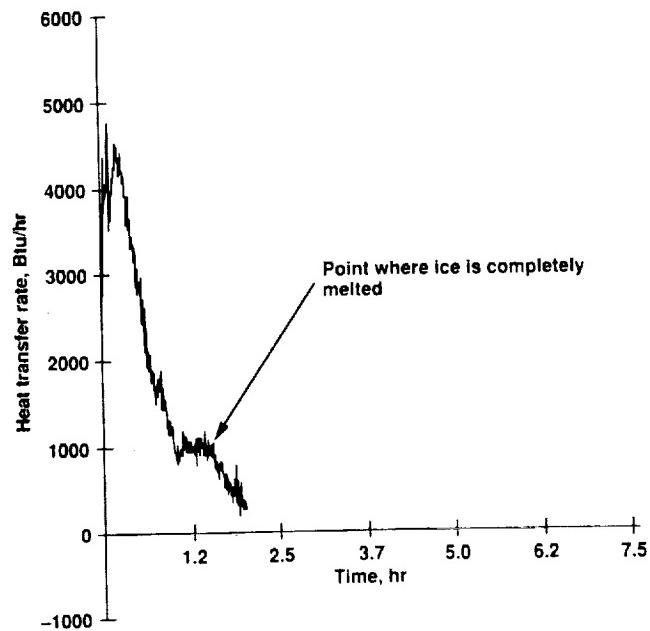
Figure 7. Heat-transfer time history of the first prototype configuration (no connectors/no baffles).
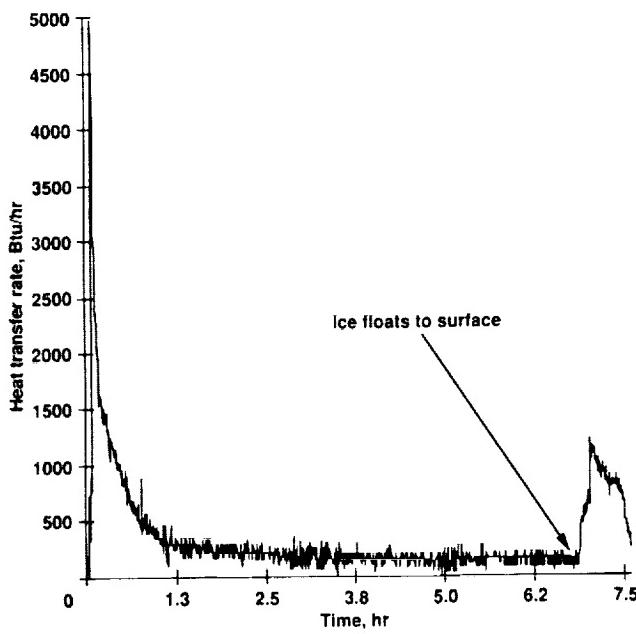
Figure 8. Heat-transfer time history of the second prototype configuration (connectors/no baffles).
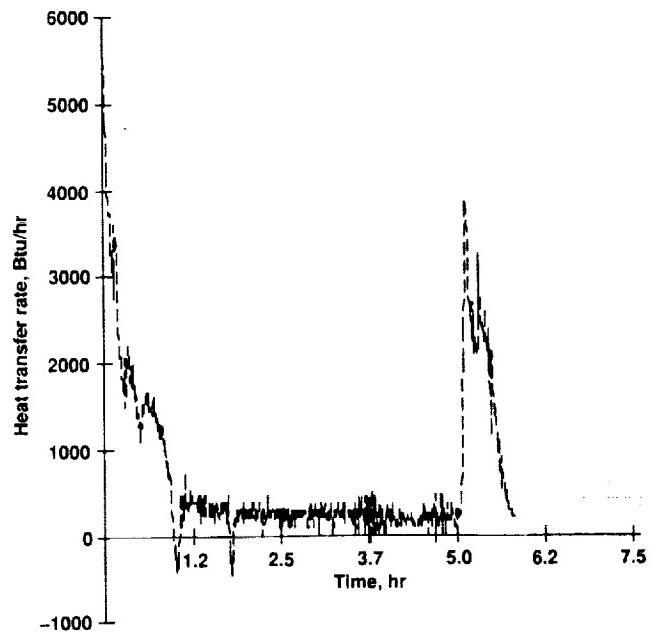

Figure 10. Heat-transfer time history of the third prototype configuration (connectors/baffles).
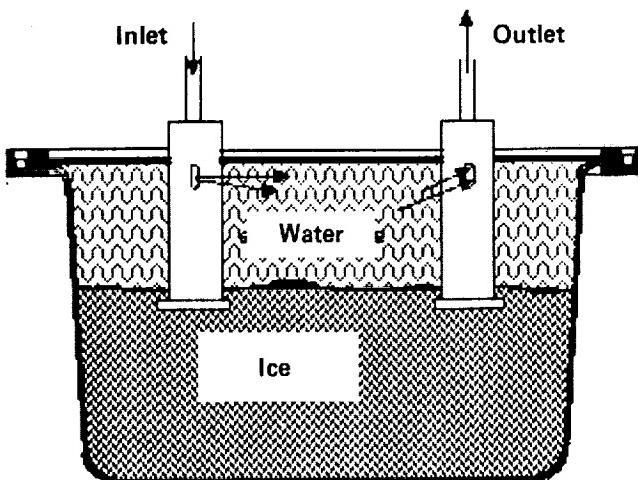

Figure 9. Channeling during melt.
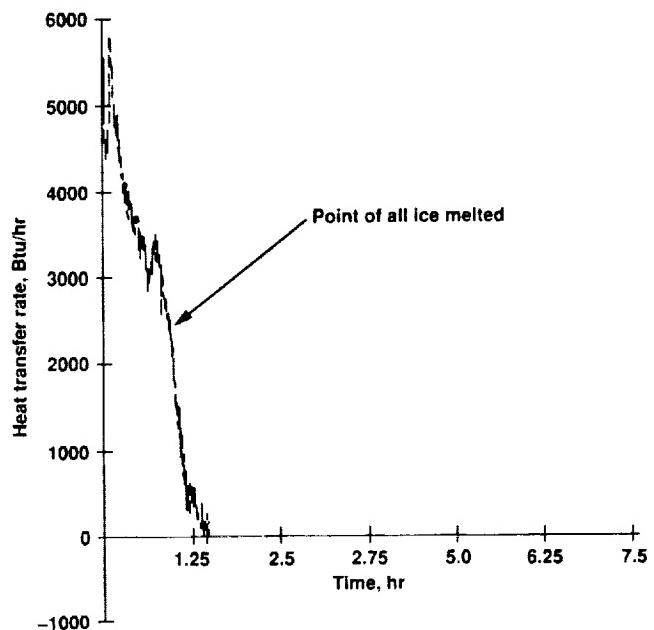
Figure 11. Heat-transfer time history of the fourth prototype configuration (connectors/no baffles/turbulent).

12

Report Documentation Page

1. Report No. NASA TM-102835	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Direct-Interface, Fusible Heat Sink for Astronaut Cooling		5. Report Date May 1990
		6. Performing Organization Code
7. Author(s) Curtis Lomax and B. W. Webbon		8. Performing Organization Report No. A-90189
		10. Work Unit No. 506-41-21
9. Performing Organization Name and Address Ames Research Center Moffett Field, CA 94035-1000		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, DC 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

Presented at SAE/ICES 20th International Conference on Environmental Systems, July 9, 1990, Williamsburg, VA
Point of Contact: Curtis Lomax, Ames Research Center, MS 239-15, Moffett Field, CA 94035-1000
(415) 604-3344 or FTS 464-3344

16. Abstract

Astronaut cooling during extravehicular activity is a critical design issue in developing a portable life support system that meets the requirements of a space station mission. Some of the requirements are that the cooling device be easily regenerable and nonventing during operation. In response to this, a direct-interface, fusible heat sink prototype with freezable quick-disconnects has been developed. A proof-of-concept prototype has been constructed and tested that consists of an elastic container filled with normal tap water and having two quick-disconnects embedded in a wall. These quick-disconnects are designed so that they may be frozen with the ice and yet still be joined to the cooling system, allowing an immediate flow path. The inherent difficulties in a direct-interface heat sink have been overcome, i.e., (1) establishing an initial flow path, (2) avoiding low-flow freeze-up, and (3) achieving adequate heat-transfer rates at the end of the melting process. The requirements, design, fabrication, and testing are discussed.

17. Key Words (Suggested by Author(s)) Astronaut cooling Phase change Heat sink Thermal regulation	18. Distribution Statement Unclassified-Unlimited Subject Category - 34		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 13	22. Price A02

NASA FORM 1626 OCT 86