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DEVELOPMENT OF A REFRIGERATION SYSTEM FOR LUNAR SURFACE AND SPACECRAFT APPLICATIONS

Contract No. NAS9-9912
Report No. T122-RP-046

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FINAL REPORT

9 April 1976

Submitted by:

VOUGHT CORPORATION
Systems Division
Dallas, Texas

To

THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Johnson Space Center
Houston, Texas

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PREPARED BY:

R J Copeland
R. J. Copeland

APPROVED BY:

R L Cox
R. L. Cox - Supervisor
EC/LS Group

FOREWORD

This is the Final Report on Contract NAS9-9912 which was executed by Vought Corporation, Systems Division in the period of December 1969 to April 1976. This is a summary report; the information presented in this report has previously been published in detail in progress reports, interim reports and briefings.

The NASA/JSC Technical monitors on this program were:

D. W. Morris for the Evaluation of Refrigeration Systems for Lunar surface and Spacecraft Application Applied to CO_2 Reactant Beds

K. L. Hudkins for the Shuttle Kit ECLSS Refrigeration Unit and Shuttle Kit Freezer.

Jim Jaax provided technical direction on the freezer.

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1.0 INTRODUCTION AND SUMMARY

In the space program refrigeration processes have not been used to date because a cold heat sink has been available in orbital flights (i.e., radiation to an effective space temperature of less than 40°F). For short durations an expendable heat sink (water boiling or sublimation) or the thermal capacity of the spacecraft systems has been utilized. Applications of refrigeration on future missions include a lunar shelter where a refrigeration cycle could be used to "top-off" in the daytime a space radiator system which was sized for lunar night operation. This would minimize radiator size and low load control requirements. Another potential use for such a system would be in lunar exploration vehicles in which there is a limited radiator area. A simple radiator would not perform adequately in deep craters or near a cliff at lunar mid-day. For long duration missions a refrigerator may also be required for storage of food and medical supplies.

All refrigeration techniques use energy to remove heat from a thermal source at a low temperature and reject heat to a thermal sink at a higher temperature. Thermoelectric devices are electrically powered and use the thermoelectric properties of solid material to perform this function with no moving components. Vapor cycles all use a power source and the properties of fluids to perform the function by absorbing the latent heat of vaporization in an evaporator at a low pressure and temperature and rejecting the latent heat of vaporization in a condenser at a higher pressure and temperature. The vapor compression cycle uses an electrical/mechanical or thermal/mechanical power source to compress the fluid between the evaporator and the condenser. The absorption and adsorption cycles primarily use thermal energy directly as a power source although electro/mechanical pumps or ejectors are sometimes used in the systems.

Vought Corporation, Systems Division performed an evaluation of these refrigeration devices for potential lunar surface and spacecraft applications. The first phase of the study selected; (1) the best refrigeration machine for several representative applications and (2) the overall best refrigeration system satisfying all applications. The latter phases of the contract evaluated three specific applications: (1) refrigeration of life support system reactant beds for the Space Station Prototype, (2) a food freezer/biomedical storage kit for Space Shuttle and (3) a kit refrigeration system to provide increased quantities of payload heat rejection from the Shuttle while in orbit.

The initial studies evaluated vapor compression cycles, vapor absorption cycles using both R-22/E-181 and water/LiBr, combined water/LiBr with an integral turbine compressor and vapor adsorption with water/13X zeolite absorbent. A conventional radiator was used as a baseline for comparative purposes. Parametric performance data were generated for each of 6 potential applications. Vapor compression was found to be the best overall choice for all applications.

Vapor compression refrigeration of life support system reactant beds was studied for a Space Station Prototype baseline system. Refrigeration does not offer a significant weight advantage over a non-refrigeration system but can eliminate solar absorbers and fluid swivels.

A conceptual design of a food freezer/biomedical sample kit for the Space Shuttle was prepared. A Stirling cycle system was selected for long life, low power and safety.

A refrigeration kit to the Space Shuttle R-21 loop was evaluated as a means of increasing the payload cooling capability. Significant increases are possible; however, deployment of conventional radiators can provide even larger increases with lower weight penalties as long as low solar absorptance coating properties can be maintained.

2.0 DISCUSSION

Contract NAS9-9912 was a study of refrigeration systems for lunar surface and spacecraft applications. In all cases the application was for a manned environmental control system, including food freezers, humidity control and payload heat rejection systems. The temperature range of interest was from less than -20°F to a 45°F to 130°F range; heat loads were from a few watts to several thousand BTU/hr.

Contracts NAS9-9912 and NAS9-12055 were conducted by Vought with NASA/JSC for the development of refrigeration systems. Because of the similarity of the two contracts, both projects were conducted as a single development program for a refrigeration system. A single document identification system was employed; Table 1 presents a list of all previous documentation on these two contracts. T122-RP-038 is the final report of NAS9-12055. The present report will discuss only results obtained under NAS9-9912.

This contract produced four summary documents on the following areas:

1) Evaluation of The Performance of Refrigeration Systems (Documented in T122-RP-04)
2) Evaluation of Refrigeration Applied to CO_2 Reactant Beds (Documented in T122-RP-06)
3) Shuttle Kit Freezer Refrigeration Unit (Documented in T122-RP-044)
4) Shuttle Kit ECLSS Refrigeration System (Results Documented in Appendix A)

The following paragraphs abstract the results in each area.

2.1 Evaluation of The Performance of Refrigeration Systems

The first phase of this contract studied the various refrigeration machines which could be used to provide heat rejection in Environmental Control Systems (ECS) for lunar surface and spacecraft applications, and to select: (1) the best refrigeration machine for satisfying each individual application, and (2) the best refrigeration machine for satisfying all of the applications. Conventional single phase pumped fluid radiators were considered in the evaluation as a baseline only: the purpose of the study was to select the best refrigeration system and not to choose between con-

TABLE 1

REFRIGERATION SYSTEM DEVELOPMENT
PROGRAM DOCUMENTATION LOG

REPORT NO.	TITLE	DATE
T122-RP01	1st Progress Report, 9 Dec. 1969 to 9 Jan. 1970(NAS9-9912)	9 Jan. 1970
-RP02	2nd Progress Report, 10 Jan 1970 to 9 Feb. 1970 (9912)	13 Feb. 1970
-RP03	3rd Progress Report, 10 Feb. 1970 to 31 March 1970 (9912)	8 Apr. 1970
-RP04	Evaluation of the Performance of Refrigeration Systems for Lunar Surface and Spacecraft Applications (9912)	15 Oct. 1971
-RP05	4th Progress Report, 1 April 1970 to 11 July 1970 (9912)	15 July 1970
-RP06	5th Progress Report, 1 June 1971 to 1 Sept. 1971 (9912)	3 Sept 1971
-TR07	Dual-Mode Refrigeration System Demonstration Test Request (NAS9-12055)	27 Sept 1971
-RP08	1st Quarterly Progress Report on Contract NAS9-12055 1 Aug. 1971 to 30 October 1971	1 Nov. 1971
-RP09	6th Progress Report; NAS9-9912 1 Sept. 1971 to 15 Feb. 1972	3 Sept 1971
-RP10	2nd Quarterly Progress Report on Contract NAS9-12055 1 Nov. 1971 to 15 Jan. 1972	15 Jan. 1972
-RP11	7th Progress Report for the Period 16 Jan. 1972 to 30 April 1972 for NAS9-9912	1 May 1972
-RP12	3rd Quarterly Progress Report on NAS9-12055; 15 Jan. 1972 to 15 July 1972	17 July 1972
-TR013	Direct Condensing Radiator Feasibility Demonstration Test (NAS9-12055)	16 Jun. 1972
-TIR013	Direct Condensing Radiator Feasibility Test (NAS9-12055)	25 Aug. 1972
-RP014	NAS9-9912 8th Progress Report - 1 May to 6 Aug. 1972	5 Aug. 1972
-RP015	Zero-g Radiator/Condenser Test Plan (NAS9-12055)	15 Sept 1972
-RP016	NAS9-9912 9th Progress Report - 1 Aug. to 15 Sept. 1972	20 Sept 1972
-RP017	Quick-Look Test Report - Ground Test of Zero-g Condensation Experiment Apparatus (NAS9-12055)	13 Nov. 1972
-RP018	NAS9-9912 10th Progress Report- 16 Sept. 1972 to 1 Dec. 1972	1 Dec. 1972
-RP019	NAS9-12055 Progress Report - 16 July to 22 November 1972	22 Nov. 1972
-RP020	Zero-g Radiator/Condenser Experiment Package Test (NAS9-12055)	14 Feb. 1973
-RP021	NAS9-9912 11 th Progress Report - 1 Dec. 1972 to 15 Apr. 1973	18 Apr. 1973

TABLE 1 (CONT'D)

REPORT NO.	TITLE	DATE
T122-RP022	Zero-g Dual Mode Radiator/Refrigeration System Test Report (NAS9-12055)	1 May 1973
-RP023	NAS9-12055 Progress Report 1 Dec. through 1 July 1973	2 July 1973
-RP024	NAS9-9912 12th Progress Report for 16 April 1972 to 1 July 1973	2 July 1973
-RP025	NAS9-9912 13th Progress Report 2 July 1973 to 14 Aug. 1973	14 Aug. 1973
-RP026	NAS9-9912 14th Progress Report 15 Aug. 1973 to 29 Sept. 1973	28 Sept 1973
-RP027	NAS9-12055 Progress Report 3 July to 5 October 1973	5 Oct. 1973
-RP028	NAS9-9912 15th Progress Report 29 Sept. to 15 Nov. 1973	15 Nov. 1973
-RP029	NAS9-9912 16th Progress Report 16 Nov. to 20 Dec. 1973	20 Dec. 1973
-RP030	NAS9-12055 Progress Report 6 Oct. to 6 Jan. 1973	6 Jan. 1973
-RP031	NAS9-9912 17th Progress Report 21 Dec. 1973 to 21 Jan. 1974	21 Jan. 1974
-RP032	NAS9-9912 18th Progress Report 22 Jan. to 28 Feb. 1974	24 Feb. 1974
-RP033	Deleted	
-RP034	NAS9-12055 Progress Report 6 Jan to 6 July 1974	9 July 1974
-RP035	NAS9-9912 19th Progress Report 1 March to 8 July 1974	9 July 1974
-RP036	NAS9-9912 20th Progress Report 9 July to 8 Aug. 1974	9 Aug. 1974
-RP037	NAS9-9912 21st Progress Report 9 Aug. to 8 Sept. 1974	9 Sept 1974
-RP038	Final Report of NAS9-12055	14 Oct. 1974
-RP039	Shuttle Kit Refrigeration System Concepts Trade-Off Review	18 Oct. 1974
-RP040	Hybrid vs Simple Kit Refrigeration System Trade-Offs	30 Oct. 1974
-RP041	NAS9-9912 Progress Report #22 9 Sept. 1974 to 1 Feb. 1975	24 Feb. 1975
-RP042	Shuttle Orbiter Freezer Kit Cooler Unit Trade-Offs, Briefing Manual	13 Feb. 1975
-RP043	NAS9-9912 23rd Progress Report 2 Feb. to 27 April 1975	28 May 1975
-RP044	Copeland, R. J., "Shuttle Kit Freezer Refrigeration Unit Conceptual Design", Final Report	22 Aug. 1975
-RP045	NAS9-9912 24th Progress Report 28 April to 8 Sept. 1975	8 Sep 1975
-RP046	Final Report of NAS9-9912	9 Apr. 1976

ventional radiators and refrigerated heat rejection systems for the specific applications.

The refrigeration machines considered in the study included:

(1) Vapor Compression Cycle (work-driven)
(2) Vapor Adsorption Cycle (heat-driven)
(3) Vapor Absorption Cycle (heat-driven)
(4) Thermoelectric (electrically-driven)
(5) Gas Cycle (both reversed Brayton and reversed Stirling cycles)(work-driven)
and (6) Steam-Jet (heat-driven)

Various working fluids were considered for each type of refrigeration machine, and a selection of working fluids was made for each machine. A preliminary screening of the types of refrigeration machines was also made, resulting in the following specific refrigeration machines and working fluids being considered in the trade study:

(1) Vapor compression using Refrigerant 12 or 22, depending on system
(2) Vapor absorption with Refrigerant 22 (R22) and Dimethyl Ether or Tetraethylene Glycol (E-181) as working fluids
(3) Vapor absorption with Lithium Bromide (LiBr) and water as working fluids
(4) Vapor absorption with LiBr/H_2O working fluids and a turbine/compressor to recover work from the absorbent flow stream
(5) Vapor adsorption using water as the refrigerant and type 13X zeolite as the solid absorbent
(6) Conventional radiator with R21 coolant (included for comparative purposes only)

A computer routine was written which calculates performance of the candidate refrigeration machines under various operating conditions. The optimum weight system for each of the candidate machines in each application can be found with this computer routine. The computer routine determines a specific weight for each machine which includes power penalty, required radiator area penalty, and thermal energy source penalty. The significant operating parameters are the effective environment heat sink temperature and the required evaporator temperature.

An Effectiveness Function was used in the refrigeration machine selection. The Effectiveness Function considers not only the optimum refrigeration system weight, but also the system volume penalty, maintenance requirements, redundancy requirements, technical risk, and development and fabrication costs. The Effectiveness Function relates these items through trade factors which are dependent on the mission (e.g., launch cost in dollars per pound, crewman time cost in dollars per hour, etc.), and accountable factors which are dependent on the particular refrigeration system (e.g., system weight in pounds, required crewman maintenance in hours, etc.). Both of these factors were estimates for the next generation of spacecraft, and for the specific refrigeration systems.

The selected refrigeration system for each mission considered is given below:

MISSION	REFRIGERATION SYSTEM
Earth Orbit	Vapor Compression(1)*
Lunar Orbit	Vapor Compression(1)
Lunar Surface Base	Vapor Adsorption Vapor Absorption, LiBr/H_2O with a turbine/compressor
Lunar Surface EVA	Vapor Compression
Transmartian	Vapor Adsorption(2) Vapor Absorption, LiBr/H_2O with a turbine/compressor
Space Shuttle(3)	Vapor Compression(4)

*Notes: (1) The conventional radiator system is superior to vapor compression unless the sink temperature is high or there is a severe shortage of available radiator area.

(2) Vapor compression is a strong third.

(3) Only the orbital portion of the Shuttle mission was considered, although the refrigeration system may well be more competitive when considered for all mission phases.

(4) For the assumed area limited situation, the vapor compression system was superior to a conventional integral radiator (even on a specific weight basis), but was inferior to a deployed conventional radiator system.

The recommended order for development of the various types of refrigeration machines was:

(1) Vapor compression because it is the superior system in near-term applications (Space Shuttle and Space Station), it is applicable to all missions, and it is the superior system in the greater number of applications.

(2) Water adsorption in zeolite, because it provides a lightweight system in hot environments, it is insensitive to radiator (condenser) coatings degradation (because of the 200°F operating temperature), it eliminates technical problems in zero-gravity refrigerant/absorbent separation common to most heat-driven refrigeration machines, and it provides a completely independent approach should any problems develop in application of the vapor compression refrigeration machine.

(3) Freon absorption using R-22 and E-181 as working fluids. This system has the advantage that it utilizes low-grade waste heat. This refrigeration machine has the disadvantage that it requires zero-gravity liquid/gas separation, and it has limited applicability.

(4) Water absorption using LiBr/H_2O working fluids with a turbine/compressor to recover energy from the absorbent flow. This is the lightest weight system for a hot environment, however, it involves great development costs and high technical risk.

This study is documented in T122-RP-04, dated 31 October 1971.

2.2 Evaluation of Refrigeration Applied to CO_2 Reactant Beds

Report T122-RP-06 presents the results of a study conducted to evaluate the use of refrigerated mole sieves in the CO_2 removal system of the Space Station Prototype (SSP). The primary purpose of the study was to determine if refrigerated systems could be designed to provide an advantage over a heated system using a solar absorber.

As a general approach to the study a baseline system was defined that could be used as a base for comparing the different system designs. In sizing the low temperature systems as many of the baseline parameters as possible were held constant. These parameters included hardware component weights, mole sieve and silica gel bed sizes, the cabin gas flow rate, the heat transport loop maximum temperature and flow rate, and the CO_2 design partial pressure and removal rate. The baseline system selected was the same as that presented by Hamilton Standard in their SSP ETC/LSS document*.

Because of the constraints imposed on hardware design and specific operating parameters, the system designs resulting from the study are non-optimum. In spite of this, these systems are only about 5-10% heavier than the baseline system. Since no solar absorber is required in the alternate systems, the problems associated with developing a suitable surface coating and a fluid swivel could be avoided.

The results of the trade study lead to the following conclusions.

(1) Low temperature mole sieve systems for CO_2 removal aboard the SSP compare favorably with the baseline system suggested by Hamilton Standard*. The total equivalent weight of these systems is quite near the baseline system weight.

(2) The baseline system operating with a vapor compression refrigeration loop to cool the adsorbing beds can be adapted to meet a CO_2 partial pressure of 1 mm Hg. The equivalent system weight is approximately 1.5 times the total weight for the baseline system which operates at P_{CO_2} of 3 mm Hg.

(3) The baseline system is not the least weight mole sieve design for a system that uses a solar absorber. Refrigerating the adsorbing mole sieve and silica gel beds allows about a 10% reduction in the total system equivalent weight.

2.3 Shuttle Kit Freezer Refrigeration Unit

Report T122-RP-044 presents the results of a conceptual design study of a refrigerated food/medical sample storage compartment as a kit to the Space Shuttle Orbiter. To maintain the -10°F in the freezer kit, an active refrigeration unit is required. Trades were conducted and an air cooled Stirling Cycle was selected. A conceptual design study verified the feasibility of the freezer kit to be built within the current Shuttle capabilities for payloads.

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* "Requirements and Constraints for a Space Station Prototype ETC/LSS" Hamilton Standard Document, Revision B, August 24, 1970.

The freezer kit contains two subsystems, the refrigeration unit (R/U) and the Storage Volume. The R/U was studied by Vought Corporation, Systems Division in parallel with a coordinated effort by the Boeing Company, Houston, Texas, who were responsible for the Storage Volume.

The freezer must provide two basic capabilities in one unit. One requirement is to store 215 lbs of food which is consumed in a 30-day period by 7 people. The other requirement is to store 128.3 lbs of medical samples consisting of both urine and feces which are collected over the same 30-day period. For health reasons the food and samples must always be separated from each other and available to the crew throughout the mission. The freezer contains four storage compartments which are sequentially emptied to minimize the weight and volume. All compartments are nominally maintained at -10°F by the air-cooled Stirling Cycle refrigerator. Figure 1 presents the characteristics of the freezer determined by the conceptual design effort.

Figure 2 presents the overall system schematic. Since the mechanics of the Stirling Cycle prohibit a distributed cold region, heat is transferred to the Stirling Cycle from the Coolanol 15 loop in the heat exchanger. The Stirling Cycle is designed for peak heat load capacity; to prevent over-cooling the food, an electrical control system is employed. The sensor provides the signal and simple "on/off" logic is used to maintain -10°F ± 10°F. Only the Stirling Cycle and fan are automatically controlled; the Coolanol pump runs continuously except when the entire freezer is shut down.

The air cooled Stirling Cycle was selected based on a trade-off of the options. From a preliminary statement of freezer requirements, a set of guidelines and constraints were established. Three heat sinks were considered; a water loop supplied to the freezer at 45°F, a water loop at 80°F, and the cabin air at a maximum of 80°F. Eight different types of refrigerators which have previously been used or are in development for spacecraft refrigeration were screened. From Stirling Cycle, Vuilleumier, Reverse Brayton, Vapor Compression (V-C), Absorption or Adsorption, Thermoelectrics (T/E), expendables and directional space radiators, three were selected for detailed evaluation. The Stirling Cycle, T/E and V-C were selected and weight, volume, power and state-of-the-art were evaluated for each. Parametric data were generated as

o TOTAL WEIGHT (WITHOUT STORED ITEMS)	70 LBS
o COMBINATION FREEZER/FOOD WEIGHT	285 LBS
o MAXIMUM ELECTRICAL POWER REQUIREMENTS	
. 200 VAC 3ϕ	206 WATTS
. 28 VDC UNREGULATED	6 WATTS
TOTAL	212 WATTS
o PEAK COOLING RATE OF R/U	75 WATTS
o R/U AVERAGE DUTY CYCLE*	69%
o TOTAL STORAGE VOLUME	4.6 FT^3
o EXTERNAL VOLUME	9.2 FT^3
o REFRIGERATION SYSTEM LIFE	8000 HOURS
o MAINTENANCE INTERVAL (SCHEDULED)	2000 HOURS
o WORKING FLUID IN STIRLING R/U	HELIUM

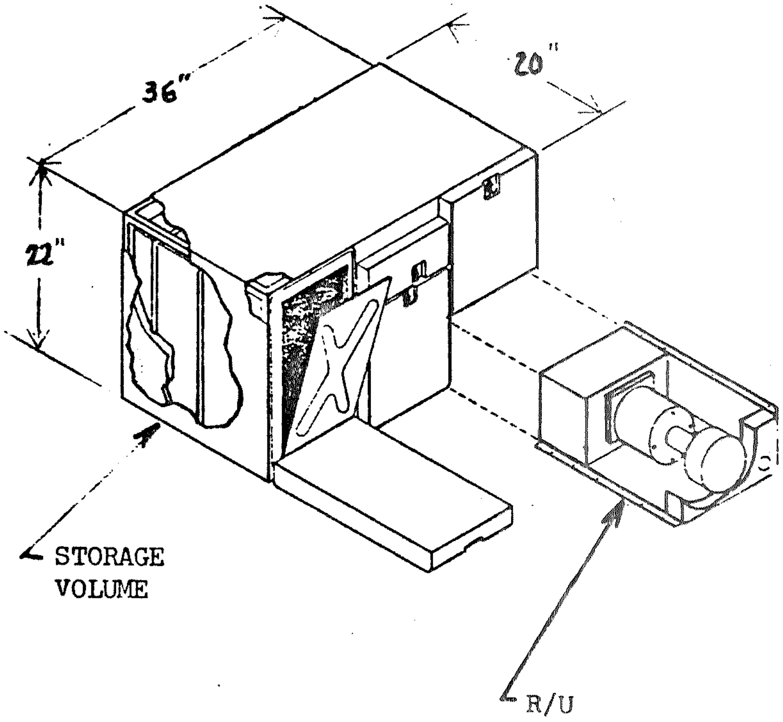

FIGURE 1

CONCEPTUAL FREEZER CHARACTERISTICS

*ON/OFF CONTROL OF THE R/U IS USED TO ACHIEVE THE AVERAGE RATE

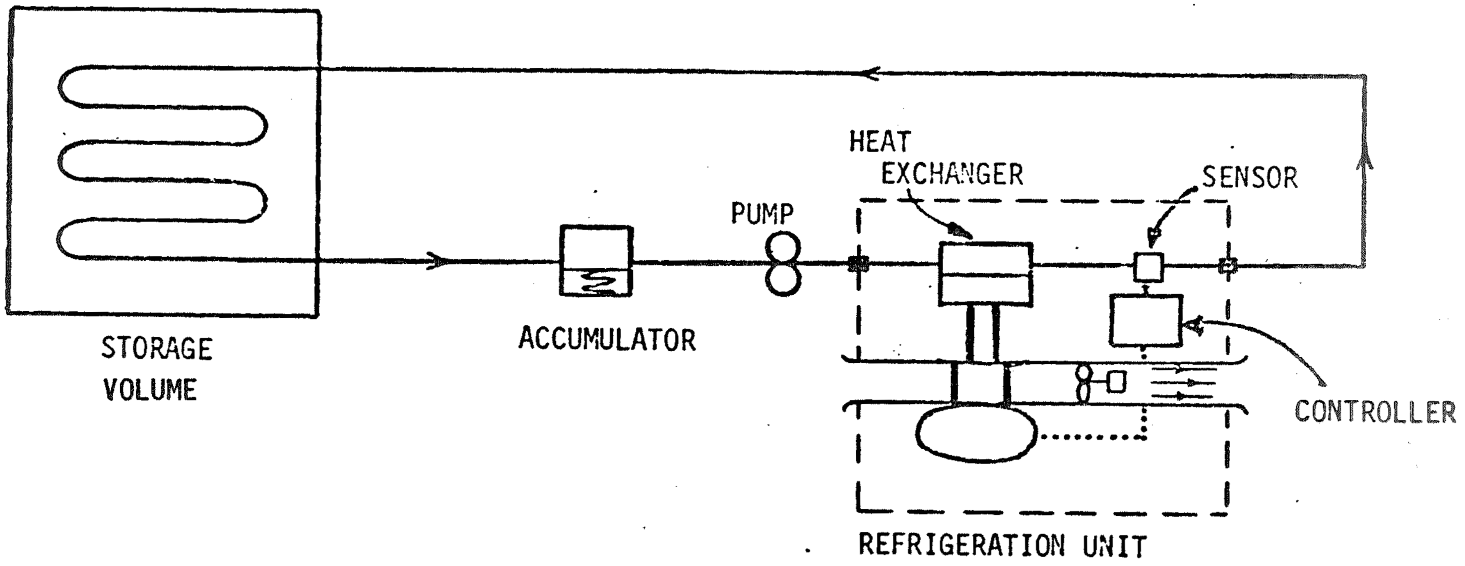

FIGURE 2

REFRIGERATION SYSTEM FEATURES

a function of cooling load for each refrigerator, allowing the insulation thickness to vary. The final selection was an air heat sink; the benefits associated with rejecting heat to the water loops were found to be less than the vehicle scar and expense associated with the complex interfaces.

The Stirling Cycle has been used previously in space. Recently, developments have pushed the state-of-the-art to one year (8000 hours) in space without any maintenance with a cryogenic application. To date no space applicable Stirling Cycle has been built in the temperature range of interest. The requirements are actually less severe than the state-of-the-art in cryogenic coolers. Technical risks do exist, particularly in power consumption, life under repeated Shuttle launches, and costs. A prototype freezer was recommended to eliminate the technical risks.

2.4 Shuttle Kit ECLSS Refrigeration System

An Environmental Control/Life Support System (ECLSS) refrigeration kit was studied to provide increased heat rejection for the Shuttle pumped fluid radiator system. The kit is a vapor compression refrigerator consisting of heat exchangers, a compressor, and associated controls and plumbing. These elements are integrated with the existing Shuttle Freon 21 coolant loops and radiators. The hardware can be installed in the Shuttle prior to launch of a payload with high cooling rate requirements; the kit is removed from the Shuttle following the flight. The kit would be located in the unpressurized cargo bay and use a Freon (R-12) as the refrigerant.

Kit refrigerator concepts to provide payload cooling were generated for two sets of groundrules:

1) No changes in the baseline Shuttle R-21 loop flow rate or temperatures.
2) One change to the baseline Shuttle R-21 loop either as an increase in flow rate or as an increase in the allowable maximum R-21 temperature into the fuel cells heat exchangers.

In both cases the extra heat load was assumed to be carried by a payload heat transport loop (assumed to be flutec pp-50, C_5F_{12}). Nominally the temperatures in that loop were 104°F out and 45°F return; other temperatures were also investigated including 130°/45°F, 75°/20°F, and 45°/0°F.

Significant increases in payload heat rejection were found for several kit refrigerator concepts. A screening process identified the most promising refrigeration concept as a simple kit which does not require alteration of the Shuttle radiators. For the first groundrule, (no changes), up to

12,000 BTU/hr can be obtained but at a penalty of 500 lbs or 28,000 BTU/hr at a penalty of 900 lbs. (104°/45° payload loop). Changing the R-21 loop groundrules reduced the penalties to 200 lbs for 9800 BTU/hr for increasing the R-21 loop temperature to 130°F or 340 lbs. for 17,000 BTU/hr for increasing the R-21 flowrate to 5800 pph.

The kit ECLSS refrigerator was compared with non-refrigeration kits (deployed radiators). For cooling a payload loop from 104°F to 45°F the results were as follows:

- Kit deployment of the aft 4 Shuttle radiators - produces 21,000 BTU/hr at 400 lbs
- Kit inflatable radiators - 16,800 BTU/hr at 150 to 300 lbs
- Self Contained Heat Rejection Module (SHRM) - 31,500 BTU/hr at 1000+ lbs

The kit ECLSS refrigerator is heavier than all but the SHRM. The same results were true when the payload return temperature was decreased to 20° and 0°F. Thus deployment of additional radiator area is more attractive, on a weight basis, than the refrigeration kit. It should be noted that this presumes that the conventional radiators maintain low solar absorptance values for their coatings. Should severe degradation occur, refrigeration systems would show a distinct advantage. When additional area can not be deployed, the kit refrigerator could be utilized. Since that condition is not overly restrictive, all further efforts on the Shuttle kit ECLSS refrigerator were terminated. The study results are presented in Appendix A of this report.

3.0 CONCLUSIONS AND RECOMMENDATIONS

3.1 Conclusions

The primary conclusions of this work are:

1) The vapor compression system is the best overall refrigeration system for lunar surface and spacecraft applications. For earth orbit applications the single phase radiator system is generally preferred more than any refrigeration system.

2) The vapor compression cycle may have some application to provide simultaneous heating and cooling. For refrigerated life support system reactant beds this approach can be weight competitive with alternative methods and can eliminate some components in other methods of obtaining heating and cooling.

3) A Stirling cycle refrigerator was selected for use inside the manned cabin of the Space Shuttle. This refrigerator presents no safety hazard to the crew and has a small power penalty. A conceptual design demonstrated the feasibility of installing/removing a kit Stirling cycle cooled food freezer within the constraints of the Shuttle.

4) Significant increases in payload heat rejection can be obtained by a kit vapor compression refrigerator added to the Shuttle R-21 loop. However deploying additional radiator area without refrigeration can achieve the same result and at a lower weight penalty as long as low solar absorptance coating properties can be maintained.

3.2 Recommendations

The following recommendations are made relative to this work:

1) Additional development of refrigeration systems for large heat loads in earth orbit use is not recommended since a deployed radiator system can usually be designed and for generally smaller penalties. However for extended exploration of the moon, a refrigerator system will be necessary.

2) For food freezer and biomedical sample storage on the Space Shuttle, a Stirling Cycle refrigerator is recommended. A prototype is needed to better define power penalties and life.

3) The best system for a food freezer/experiments compartment for an earth orbit space station has not been determined. Additional study of very long life systems for that application is recommended.

4) Additional study of Shuttle radiators with degraded solar absorptance and the potential advantage of a refrigeration system are recommended.

4.0 REFERENCES

(1) Modification 3C to Contract NAS9-9912, NASA-JSC PR-069-018, dated 12 April 1971.

(2) Modification 3S to Contract NAS9-12055, "Development of a Shuttle Orbiter Mechanical Refrigeration System", dated 16 June 1972.

(3) Modification 9C to Contract NAS9-9912, NASA-JSC PR-4-177-063, dated 17 July 1974.

APPENDIX A

SHUTTLE KIT ECLSS REFRIGERATION SYSTEM

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APPENDIX A

SHUTTLE KIT ECLSS REFRIGERATION SYSTEM

A-1.0 SUMMARY AND INTRODUCTION

An Environmental Control/Life Support System (ECLSS) refrigeration kit was studied to provide increased heat rejection for Shuttle payloads. The kit is a vapor compression refrigerator consisting of heat exchangers, a compressor, and associated controls and plumbing. These elements are integrated with the existing Shuttle Freon 21 coolant loops and radiators. The hardware can be installed in the Shuttle prior to launch of a payload with high cooling rate requirements; the kit is removed from the Shuttle following the flight. The kit is located in the unpressurized cargo bay and uses Freon (R-12) as the refrigerant.

Kit refrigerator concepts to provide increased payload cooling were generated for two sets of groundrules:

1) No changes in the baseline Shuttle R-21 loop flow rate or temperatures.
2) One change to the baseline Shuttle R-21 loop either as an increase in flow rate or as allowable maximum R-21 temperature into the fuel cells heat exchangers.

In both cases the extra heat load was assumed to be carried by a payload heat transport loop (assumed to be flutec pp-50, C_5F_{12}). Nominally the temperatures in that loop were 104°F out and 45°F return; other temperatures investigated included 130°/45°F, 75°/20°F, and 45°/0°F.

Significant increases in payload heat rejection were found for several kit refrigerator concepts. A screening process identified the most promising refrigeration concept as a simple kit which does not require alteration of the Shuttle radiators. For the first groundrule, (no changes), up to 12,000 BTU/hr can be obtained but at a penalty of 500 lbs or 28,000 BTU/hr at a penalty of 900 lbs.(104°/45° payload loop). Changing the R-21 loop groundrules reduces the penalties to 200 lbs for 9800 BTU/hr for increasing the R-21 loop temperature to 130°F at the fuel cells (flowrate of 5000 pph) or 340 lbs for 17,000 BTU/hr for increasing the R-21 flowrate to 5800 pph (112°F at fuel cells).

The kit ECLSS refrigerator was compared with non-refrigeration kits (deployed radiators). For cooling a payload loop from 104°F to 45°F the results were as follows:

- Kit deployment of the aft 4 Shuttle radiators which produces 21,000 BTU/hr at 400 lbs.
- Kit Inflatable Radiators - 16,000 BTU/hr at 150 to 300 lbs.
- Self Contained Heat Rejection Module (SHRM) - 31,500 BTU/hr at 1000+ lbs.

The kit ECLSS refrigerator is heavier than all but the SHRM. The same results were true when the payload return temperature was decreased to 20° and 0°F. Thus deployment of additional radiator area is more attractive, on a weight basis, than the refrigerator kit. This conclusion presumes that the conventional radiators maintain low solar absorptance values. Should severe coating degradation occur, refrigeration concepts would show a distinct advantage. When additional area can not be deployed, the kit refrigerator could be utilized. Since that condition is not overly restrictive, all further efforts on the Shuttle kit ECLSS refrigerator were terminated.

A-2.0 KIT ECLSS REFRIGERATOR GROUNDRULES

The kit ECLSS refrigerator must provide an increase in the payload heat rejection of the Space Shuttle Orbiter while not affecting other capabilities. The increase is limited to on-orbit applications with the baseline Shuttle systems providing all cooling in all other phases of the mission.

Concepts were generated for two sets of groundrules. One set required that the Shuttle R-21 flow loop be affected to the absolute miminum, i.e., no change in flow rate and temperatures other than in the radiators. The second set allowed a change either in the R-21 flow rate or temperatures in the system. In the first set the kit refrigerator will have a very small scar on the vehicle but unfortunately results in rather large weight penalties. The second set of groundrules reduced the weight penalties at the expense of system complexity and vehicle scar.

Figure A-1 presents the Shuttle baseline Freon 21 (R-21) coolant loop and radiators. When in orbit the radiators are the primary means of heat rejection. In hot environments and during maximum heat rejection periods

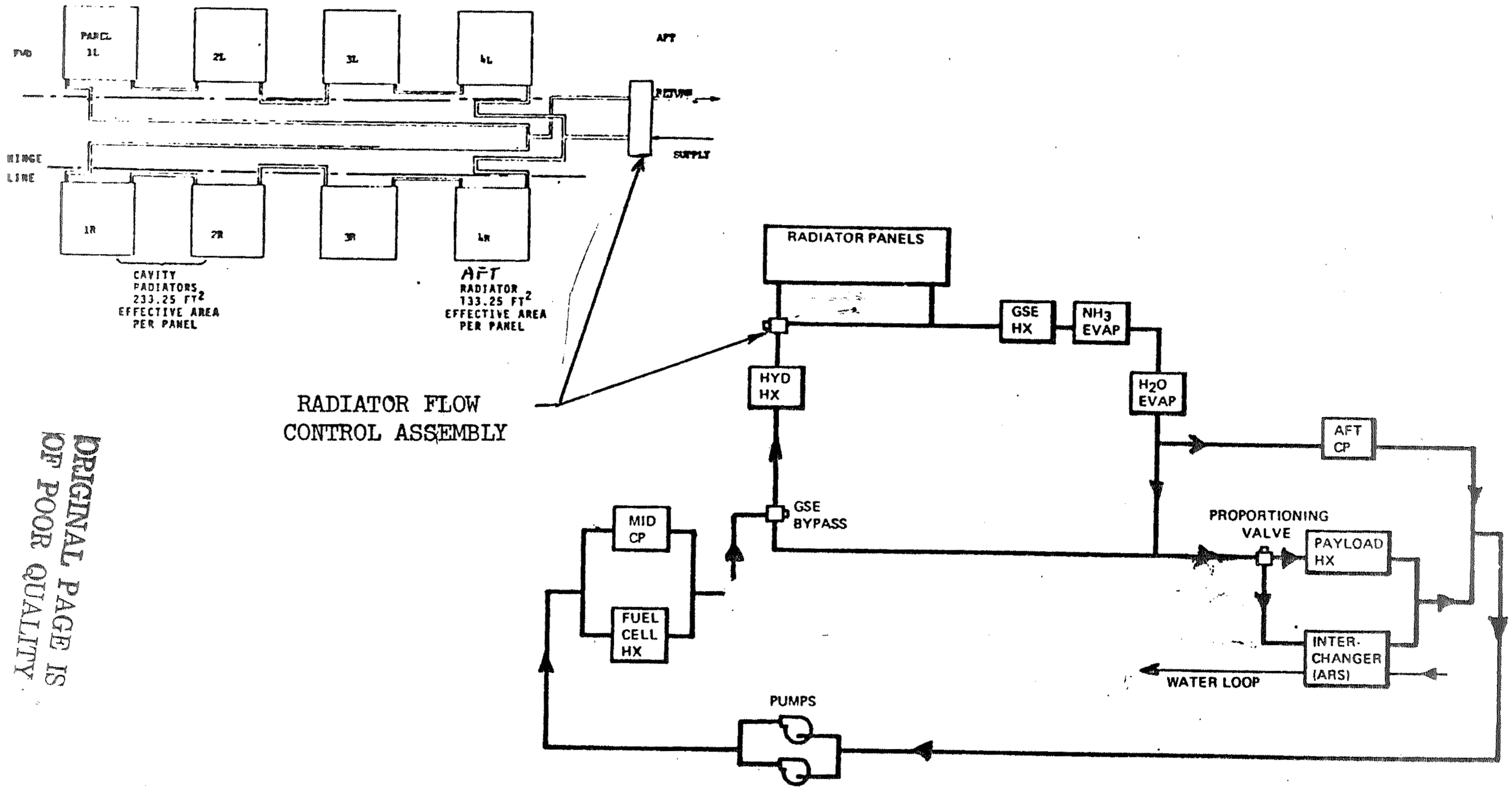


FIGURE A-1
FREON COOLANT LOOP (TYPICAL LOOP 1 AND LOOP 2)

the H_2O evaporator cools the Freon to 38 ± 2°F by evaporating fuel cell product water. The Ground Support Equipment (GSE) heat exchanger is used only when the Shuttle is on the ground. The NH_3 evaporator is used during launch and re-entry periods. The aft cold plate cools electrical/electronic equipment in the aft portion of the Shuttle; and the mid cold plate cools equipment in the mid-section of the vehicle. The fuel cells generate all power for on-orbit operations and are cooled by the Freon loop.

The payload heat exchanger is cooled by the Freon loop. Two different levels of payload heat rejection are standard on the Shuttle as follows:

. 6 radiators in the loop, R-21 flow rate of 4500 pph	21,500 BTU/hr with payload transport loop at 130°F in, 45°F return
. 8 radiators in the loop, R-21 flowrate of 5000 pph	29,000 BTU/hr with payload transport loop at 104°F in, 45°F return

The Atmospheric Revitilization System (ARS) interchanger removes heat from the water loop which flows through the pressurized cabin. The proportioning valve controls the flow split between the payload HX and the ARS interchanger. That valve increases the flow of Freon in the ARS interchanger during launch and re-entry. The additional cooling capacity removes the high heat loads generated by the electronics in the cabin. Simultaneously the proportioning valve reduces the cooling rate of payloads, which are not activated during launch and re-entry. Small payload heat loads exist during that period, and that cooling capability must not be affected by any kit system.

Six or eight radiator panels can be on the vehicle, four on each side of the cargo bay. The forward two on each side (total of four) are deployed away from the cargo bay doors. These four forward radiators are the cavity radiators which are two sided devices. Each forward radiator has an effective area (as a single sided radiator) of 233.25 ft^2. The four aft radiators are truely single sided. The effective area of each aft panel is 133.25 ft^2. The total radiating area of all eight radiators is 1466.0 ft^2. When only 6 radiators are present, the furtherest aft radiator on each side are removed, leaving 4 forward cavity radiators and 2 aft - total area of 1199.5 ft^2. All radiators are coated with silver backed Teflon.

Two Freon coolant loops (loop 1 and loop 2) flow continuously to provide redundancy. Each loop carries half of the total system flow rate of 5000 lb/hr of R-21 (2500 pph per loop).

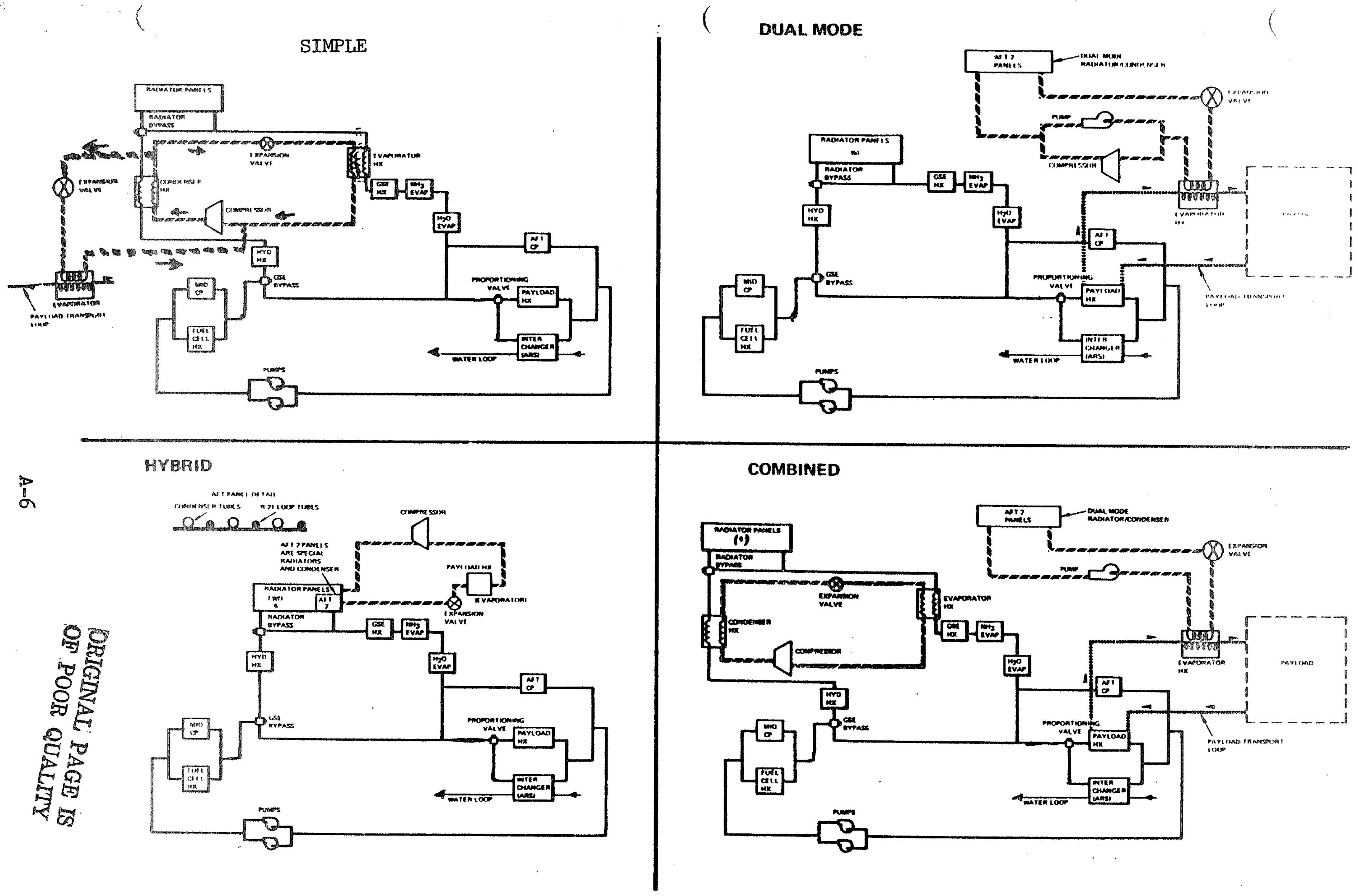
The baseline Shuttle has only four radiators which are two-sided. All eight panels can be made into two-sided radiators by an appropriate kit. The kit would increase the vehicle weight by 400 lbs. for a development mechanism, fluid routing changes and increases in the panel weight. When all panels are two-sided, the old aft panels must also be replaced with a new set of similar to the forward panels.

A-3.0 KIT ECLSS REFRIGERATOR CONCEPTS FOR NO CHANGES TO SHUTTLE R-21

Figure A-2 presents the four basic types of kits considered in this study. In all cases the temperature of R-21 is 38 ± 2°F at the flash evaporator outlet and the temperature of the R-21 leaving the fuel cells is the same as one of the standard flow rate conditions.

The "Simple" system requires one condensor and two evaporators in the system. One evaporator is in the payload loop with its own expansion valve which operates on/off to meet the actual heat load of the payload. The condenser is in the R-21 loop downstream of the fuel cells, raising the inlet temperature to the radiators. Due to the higher temperature the radiators reject more heat but also have a higher outlet temperature. The refrigerator evaporator in the R-21 loop removes part of the excess heat. The remainder of the heat is removed by the evaporation of fuel cells product water. The R-21 leaving the H_2O evaporator is controlled to 38 ± 2°F. Each refrigeration evaporator is individually controlled with an expansion valve to meet actual heat loads and environment conditions.

The "dual mode" and "hybrid" concepts will produce equal increases in payload heat rejection; the only difference is heat load control methods during low load and in cold environments. Both concepts utilize a R-21 flow rate of 4500 pph in six radiator panels. The futherest aft two (one on each side of the vehicle) are dedicated to the refrigeration loop. These two panels are the condenser in the refrigeration loop. The evaporator heat exchanger is in the payload loop, downstream of the payload heat exchanger. Alternatively



BASIC KIT ECLSS REFRIGERATOR CONCEPTS

FIGURE A-2

the payload transport loop may be divided with part of the flow into the payload heat exchanger; the remainder flows into the evaporator.

The dual mode approach achieves low load control with a pumped fluid loop. The compressor is deactivated and a liquid pump provides fluid circulation. The same tubes are used in both the refrigeration and pumped fluid modes. An accumulator (not shown) provides the change in fluid volume between the two modes.

The hybrid approaches achieves low load control utilizing the Shuttle R-21 loop. The aft two panels are equipped with a set of tubes for the refrigeration system and an independent set containing the R-21 loop. During peak heat loads, bypass valves divert the R-21 loop away from the aft 2 panels. During low load the refrigeration loop is deactivated and the R-21 flows through all eight panels. No accumulator is required. In both the hybrid and dual mode the aft 2 radiators replace the basic shuttle radiators with ones specifically designed for that application.

The "combined" concept uses elements of both simple system and the dual mode system. In this concept the R-21 flow rate is 5000 pph but only flows through 6 radiator panels. The refrigerator is configured to cool the radiator outlet by rejecting heat to the R-21 loop upstream of the radiator inlet. The high temperature radiators now reject the total Shuttle baseline heat loads with only the six panels. The aft 2 panels (one on each side) are free to provide increased heat rejection with a single phase pumped fluid loop.

Four Panel Shuttle R-21 Loop

In all of the previous concepts either 6 or 8 radiators were connected to the R-21 loop. Four radiators can also be utilized to cool the Shuttle heat loads. In that condition, only a small quantity of payload heat load is removed via the Shuttle R-21 loop. The reduced heat load can be rejected by only the four forward, cavity radiators. The aft four radiators are available to reject payload heat. All of the four basic types of refrigerators can be used with only 4 radiators in the R-21 loop. Obviously the 4 panel system can be used when the 4 aft panels are also deployed to make cavity, two-sided radiators (i.e., when all 8 panels are cavity radiators). An example kit refrigeration system is shown in Figure A-3.

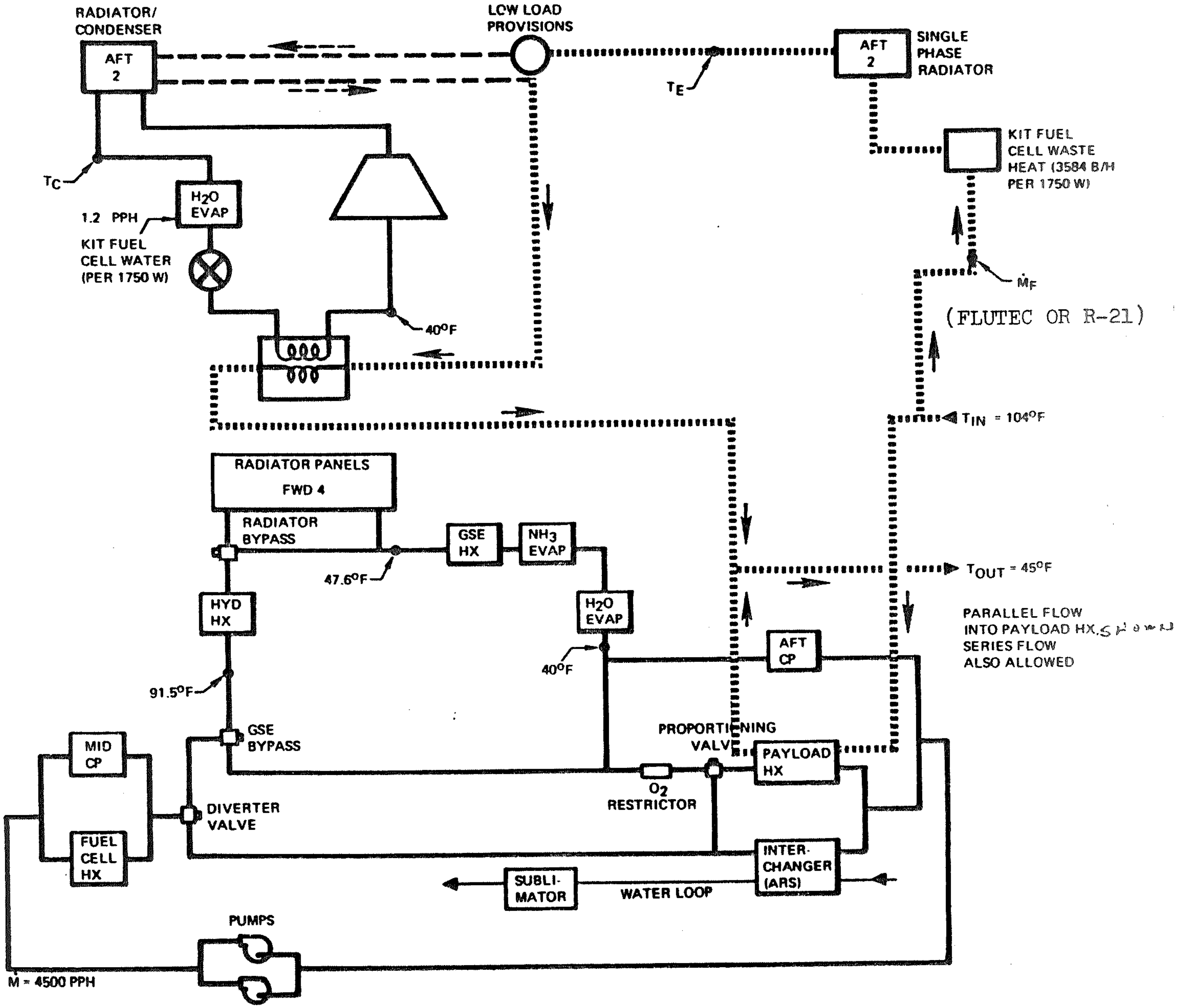


FIGURE A-3

FOUR PANEL SHUTTLE R-21 LOOP

(HYBRID SHOWN, OTHERS ARE POSSIBLE)

A-3.1 INITIAL SCREENING

An initial screening was conducted to eliminate obvious non-competitive refrigeration concepts. The groundrules were established so that the power was the same in all cases and the fixed refrigeration elements were known to be very close in weight. Thus only the quantity of increase heat rejection was required to identify the relative merits of each system. Reference A-1 presents the details of this screening. The results are summarized in Table A-1. All concepts have 8 radiators on the Shuttle. Two conditions are considered in Table A-1: (1) No change to the Shuttle radiators, i.e., total radiating area of 1466 ft^2 and (2) all radiators are two-sided cavity radiators, total radiating area of 1866 ft^2. Concepts were analyzed for each of the four basic refrigeration types with both radiator configurations. When appropriate, the results were calculated for both 4 radiators in the Shuttle R-21 loop or 6 radiators in the Shuttle R-21 loop. The "simple" refrigeration system has the highest increase in payload heat rejection when the Shuttle radiators are unaltered. The "hybrid" has the highest when all radiators are two-sided. A more indepth study was conducted on those two concepts.

A-3.2 SIMPLE VS HYBRID TRADE-OFFS

Reference A-2 presents the results of the Hybrid vs Simple refrigeration system trade-offs. The results are summarized in Table A-2 for 1) unchanged Shuttle radiators and 2) all radiators two-sided. Each concept is optimized at different power requirements and the weight penalty calculated accordingly. The "simple" system has all 8 radiators in the R-21 loop but "hybrid" and "no refrigeration" only have 4 radiators in the R-21 loop. The "hybrid has two radiators as condensers and two as flutec radiators. The "no refrigeration" concept has no refrigeration system and simply routes the payload transport loop onto the aft panels. The quantity of increased heat rejection over the Shuttle basic of 29,000 BTU/hr is present in the column identified as $Q_{INCREASE}$. The required power and the power penalty is also included for 1) a special kit of fuel cells to provide power or 2) assumed usage of the basic Shuttle fuel cells with a kit for fuel cell reactants only. The total weight includes refrigeration equipment (compressor, evaporators, heat exchangers, lines, etc.), power penalty and radiator deployment mechanism if appropriate. The specific cooling penalty is simply the weight

TABLE A-1

INITIAL SCREENING OF KIT REFRIGERATOR CONCEPTS

CONCEPT	INCREASE IN PAYLOAD HEAT REJECTION	
	4 FWD RADIATORS: CAVITIES 4 AFT RADIATORS: SINGLE-SIDED	ALL 8 SHUTTLE RADIATOR AND CAVITIES
SIMPLE		
All 8 radiators in R-21 Loop	11,800 B/H	26,000 B/H
HYBRID OR DUAL MODE		
. 6 Radiators In Shuttle R-21 Loop		
- 2 Aft Radiators As condensors	9,500 B/H	23,800 B/H
. 4 Radiators In Shuttle R-21 Loop		
- 4 Aft Radiators As Condensors	6,000 B/H	12,760 B/H
- 2 Radiators as Condensors & 2 As Flutec Rad.	5,400 B/H	28,800 B/H
- No Refrigerator-All Aft 4 as Flutec Radiators	3,500 B/H	21,300 B/H
COMBINED		
. 6 FWD Radiators In R-21 Loop		
- 2 Aft Panels as Flutec Radiators Refrigerator in R-21 Loop	10,000 B/H	21,400 B/H (refrigeration not required)
- No Refrigerator - Aft 2 as Flutec Radiators	2,400 B/H	21,400 B/H

[*] For 104°F/45°F in flutec payload loop, increase in heat rejection above Shuttle baseline heat load of 29,000 B/H (i.e., simple can provide 40,800 B/H total cooling to a payload). All concepts are power limited to 1750 watts (electrical) including 3584 B/H of waste heat and 1.2 pph of fuel cell product water.

TABLE A-2

TRADE-OFF OF HYBRID VS SIMPLE REFRIGERATION CONCEPTS

CONCEPT		$Q_{INCREASE}$ (BTU/HR)	POWER PENALTY(3) (LBS)		TOTAL WEIGHT (LBS.)		SPECIFIC COOLING PENALTY (LBS/1000 BTU/HR)	
			ALL KIT	SHUTTLE	ALL KIT	SHUTTLE	ALL KIT F.C.	SHUTTLE F.C.
4 Aft Not Deployed (Single Sided)	SIMPLE	11,800 @ 1750 watts	750	273	980	503	83.0	42.6
	HYBRID (4)	11,800 @ 3500 watts	1500	546	1700	790	144	63.2
4 Aft Deployed (Two sided) (400# for impact to rad. & deployment system)	SIMPLE	26,000 (5,100)[2] @ 1750 watts	750	273	1380	903	52.9	34.6
	HYBRID (4)	28,000 (7,100)[2] @ 1750 watts	750	273	1350	873	48.2	31.2
	NO REFRIG. (5)	21,000 @ 0 watts	-	-	400	400	19.0	19.0

NOTES:
1) @104°F inlet and 45°F return to payload
2) No refrigeration is 21,000 BTU/hr for deployment of aft 4 panels
3) For 5 day equivalent use
    - 430 lb/kw for kit fuel cells
    - 156 lb/kw for use of shuttle fuel cells
4) Flutec in radiators
5) Flutec in 4 aft radiators

of the system divided by the increase in cooling achieved.

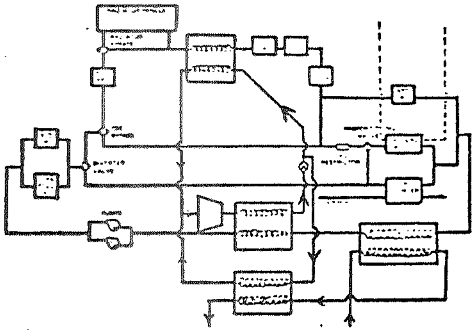
The lightest weight system is the no-refrigeration - 4 aft radiators deployed to make two-sided radiators. To implement that approach requires no new developments and thus has virtually no technical risks. The cost is likely to be cheaper than any refrigeration system. Refrigeration systems which do not affect the R-21 loop are obviously non-competitive with a deployed radiator system. Altering that groundrule could affect the conclusion. The next section presents the results of the trades when the Shuttle R-21 loop is increased in either flow rate or temperature.

A-4.0 KIT ECLSS REFRIGERATOR CONCEPTS FOR ONE CHANGE IN EITHER SHUTTLE R-21 LOOP FLOW RATE OR TEMPERATURE

Concepts were generated for two R-21 loop flowrates, 5000 pph and 5800 pph. The two flowrates represent two different Shuttle fuel cell requirements. At 5000 pph the fuel cells must be able to operate for long period of time at 130°F outlet R-21 loop temperature. The Shuttle does operate the R-21 loop temperatures up to 132°F (Reference A-3) which are currently limited to Ascent/Entry periods. If a low R-21 loop temperature out of the fuel cell heat exchanger is required, a R-21 flowrate of 5800 pph will maintain a temperature of 112°F. The temperature limit for long term use had not been resolved at the time of this work and thus both temperatures were evaluated.

Figures A-4 and A-5 present the concepts evaluated for the two flowrates. The added heat exchangers are designed for very low pressure drop so that very little change in the Shuttle baseline flowrate of 5000 pph will occur. The 5800 pph is achieved by the addition of a pump kit in each R-21 loop to raise the total system flowrate.

The four basic types of concepts are identified as "evaporator upstream of flash evaporator", "evaporator downstream of flash evaporator", "dual compressors", and "moved flash evaporator". The primary differences are the location of the refrigeration components in the Shuttle R-21 loop. The quantity of increased payload heat rejection and the specific penalty were calculated as a function of the temperature level of the payload heat

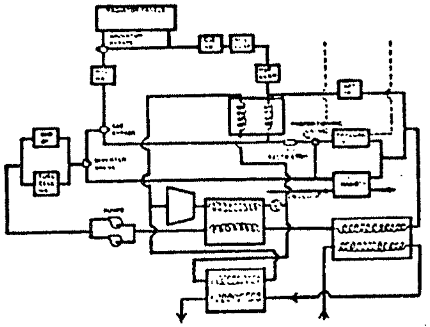


Q/W = 32.2 w/kg

$Q_{INCREASE}$ = 17,000 B/H

WEIGHT PENALTY = 340#

EVAPORATOR UPSTREAM OF FLASH EVAPORATOR CONCEPT

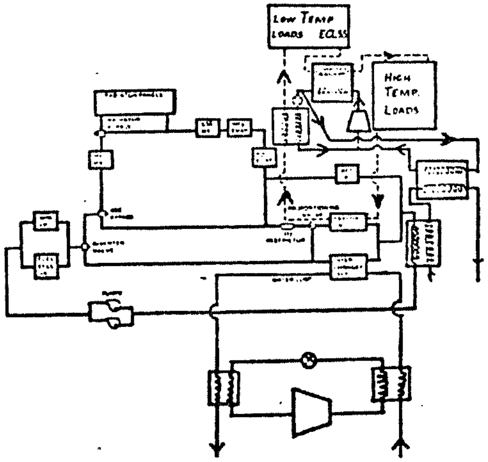


Q/W = 32.6 w/kg

$Q_{INCREASE}$ = 17,000 B/H

WEIGHT PENALTY = 336#

EVAPORATOR DOWNSTREAM OF FLASH EVAPORATOR CONCEPT



Q/W = 36.1 w/kg

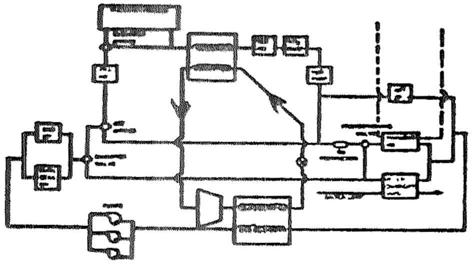
$Q_{INCREASE}$ = 18,500 B/H

WEIGHT PENALTY = 330#

DUAL COMPRESSOR CONCEPT

KIT ECLSS REFRIGERATOR CONCEPT WITH R-21 FLOWRATE OF 5000 LB/HR
FUEL CELL OUTLET TEMPERATURE = 130°F
$Q_{INCREASE}$ AS 45° RETURN TO PAYLOAD, 104°F SUPPLY

FIGURE A-4

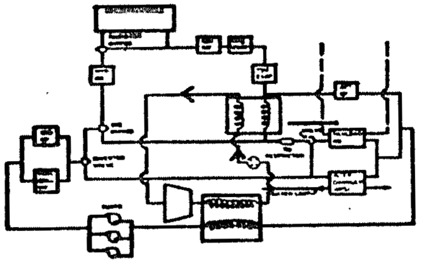


Q/W = 31.6 w/kg

$Q_{INCREASE}$ = 9800 B/H

WEIGHT PENALTY = 200 lbs

EVAPORATOR UPSTREAM OF
FLASH EVAPORATOR CONCEPT

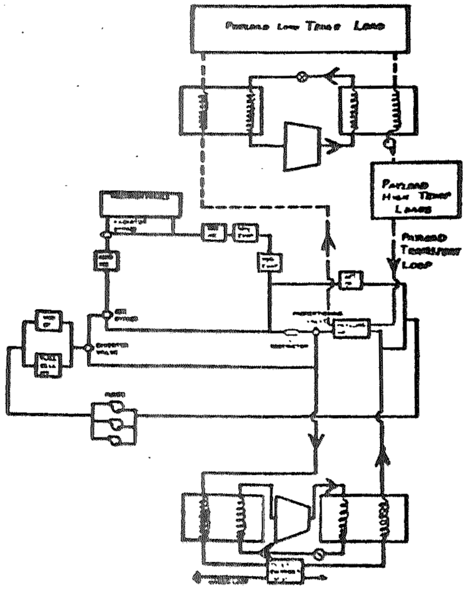


Q/W = 29.2 w/kg

$Q_{INCREASE}$ = 9500 B/H

WEIGHT PENALTY = 210 lbs

EVAPORATOR DOWNSTREAM OF
FLASH EVAPORATOR CONCEPT

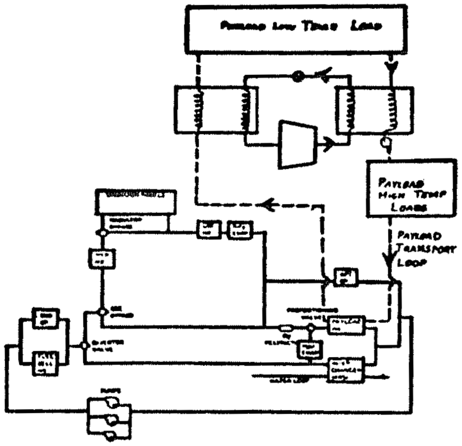


Q/W = 26 w/kg

$Q_{INCREASE}$ = 10,000 B/H

WEIGHT PENALTY = 248 lbs

DUAL COMPRESSOR CONCEPT



Q/W = 26.1 w/kg

$Q_{INCREASE}$ = 9300 B/H

WEIGHT PENALTY = 230 lbs

MOVED FLASH EVAPORATOR CONCEPT

KIT ECLSS REFRIGERATOR CONCEPTS WITH R-21 FLOWRATE OF 5800 LB/HR

FUEL CELL OUTLET TEMPERATURE = 112°F

$Q_{INCREASE}$ AS 45° RETURN TO PAYLOAD, 104°F SUPPLY

FIGURE A-5

transport loop (Reference A-4). The 5000 pph flow provided more heat rejection and a lower penalty than the 5800 pph; but may not be allowable (as previously noted). The increased quantity of heat rejection was not a very strong function of the payload temperature. That effect is due to the fact that the quantity of power for refrigeration is low and the heat rejection rate is limited by the radiator. The individual differences between the concepts in heat rejection and weight penalty were not large. The decision on the concept for the Shuttle can thus be made based on factors other than performance.

A-4.1 Evaluation of Kit ECLSS Concepts

Table A-3 presents an evaluation of the four concepts, for both the 5000 and 5800 pph flowrates. payload temperature levels for each concept are also included. As noted previously the heat rejection rate and specific penalty is similar in all cases. The column of modifications to Shuttle R-21 loop denotes that changes must be made to the Shuttle. For the "evaporator upstream of the flash evaporator", only the addition of lines and low pressure drop heat exchangers are necessary. The "evaporator downstream of the flash evaporator" requires a modification to the flash evaporator control temperature to 45°F in lieu of 37° ± 2°F. The modification to the controls must change the outlet temperature of the flash evaporator in flight. (The Shuttle currently has two control points; 37° ± 2°F (top-off mode) and 60°F (water evaporation mode); a third control point would be required.) The "dual compressor" requires the same modifications to the controls plus extra lines to provide space for extra heat exchangers. The "moved flash evaporator" requires the same modification to the controls, additional lines up and down the length of the cargo bay, and heat exchangers.

Clearly the refrigeration system upstream of the flash evaporator requires the least amount of changes to the Shuttle. That concept was selected for comparison with other kit heat rejection systems.

A-4.2 Comparison of Kit Heat Rejection Systems

Table A-4 presents a comparison of different systems to reject

TABLE A-3

EVALUATION OF KIT ECLSS REFRIGERATOR CONCEPTS

CONCEPT	$Q_{INCREASE}$* @ R-21 FLOW 5000/5800 PPH (BTU/HR)	SPECIFIC COOLING** @ R-21 FLOW 5000/5800 PPH (WATTS/Kgm)	MODIFICATION TO SHUTTLE R-21 LOOP
EVAPORATOR UPSTREAM OF FLASH EVAPORATOR			
45°F/104°F	17,000/9,800	32.2/31.6	NONE
EVAPORATOR DOWNSTREAM OF FLASH EVAPORATOR			X
45°F/104°F	17,000/9,500	32.6/29.2	
DUAL COMPRESSOR			X
45°F/104°F	18,500/10,000	36.1/26.0	
MOVED FLASH EVAPORATOR			X
45°F/104°F	- /9,300	- /26.1	

* Over shuttle basic capability

** Including power penalty @ 0.155 lbs/watt(electrical) for 96 hours of peak load use.

TABLE A-4

COMPARISON OF PAYLOAD HEAT REJECTION SYSTEMS

SYSTEM	HEAT REJECTION PER UNIT WT., Q/WT $\frac{LBS}{1000\ BTU/HR}$	$(\frac{W}{kg})$
SHRM Radiator Mode (31,500 B/H per wing)	32.7	19.7
SHRM Refrigeration Mode (35,000 B/H per wing)	48.1	13.4
Inflatable Radiator (16,800 B/H)	8.25/15.9	78.1/40.4*
Kit Deployment of Aft Radiator Panels Only (21,000 B/H)	19.1	33.8
Kit ECLSS Refrigerator		
5000 pph R-21 Flow (17,000 B/H)	20.0	32.2
5800 pph R-21 Flow (9,800 B/H)	20.4	31.6

NOTE:
1. Heat rejection is based on 370 km orbital altitude in worst orientation for each system.
2. Heat rejection is the increase in payload cooling at 104°F/45°F over shuttle basic (8 panel) of 29,000 B/H.
3. Refrigerator power penalty is 0.155 lb/w for use of shuttle fuel cells (penalty for expendables only)

* Inflatable radiator soft tube/hard tube

payload waste heat. All system weights have been normalized to the same basis; 104°F supply, 45°F return in a payload loop. All of the heat rejection attributed to each system is the increase over the Shuttle's basic 8-panel capability of 29,000 BTU/hr at 104°F/45°F in the payload transport loop. The data for SHRM and Inflatables have been updated for the latest information, and all systems have been placed on this basis (same payload loop temperatures and power penalties).

The kit ECLSS refrigerator is among the lowest penalty systems for cooling at 104°/45°F. The lowest weight system is the soft-tube inflatable radiator; kit deployment of the Shuttle aft radiators, the hard tube inflatable radiator, and kit ECLSS refrigerators have very similar penalty factors (within the calculation error of these data). The choice of the best concept is thus independent of the weight penalty and instead will depend upon other considerations. These factors include quantity of heat rejection required, capability to deploy out of the cargo bay, scar on the vehicle, and capability for low temperature cooling. The latter requirement was also evaluated for each concept (Reference A-4). All concepts provided a good heat rejection at 20°F and 0°F. With a 0°F return the kit ECLSS refrigerators and Inflatable Radiators have the lowest penalty, then the SHRM radiator and refrigerator modes and the kit deployment of the Shuttle aft radiator panels. At 20°F return the inflatable radiators have a lower weight than the kit ECLSS refrigerator, SHRM and finally the kit deployment of the Shuttle aft radiators. Again the weight differences between the concepts are not large, and the weight is probably acceptable in all cases. The choice of cooling system even for low temperature payload cooling will be based on consideration other than weight.

A-5.0 KIT ECLSS REFRIGERATOR CONCLUSIONS

The kit ECLSS refrigeration system is a viable system for increased payload heat rejection. Good heat rejection is obtained at 104°/45°F, 75°/20°F, and at 45°/0°F payload loop temperature. The specific weight penalty is as good or better than the competing systems. In addition the kit ECLSS system does not require deployment of radiators out of the cargo bay.

The kit ECLSS refrigeration concepts were evaluated for both 130° and 112°F fuel cell temperature limits (R-21 loop temperatures and flowrates of 5000 pph and 5800 pph). The concept with the refrigerator evaporator upstream of the flash evaporator and the condensor and payload heat addition upstream of the fuel cell heat exchanger was selected as the most promising. However, no strong advantage for the kit ECLSS refrigerator is present with either groundrule. The system is more complex and has a higher technical risk than deployed radiators. Thus further work on the concept was terminated.

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A-4 Copeland, R. J., "Progress Report No. 23", Contract NAS9-9912, Vought Report T122-RP-043, dated 28 August 1975.