FINAL REPORT

ELECTRIC AND HYBRID VEHICLE ENVIRONMENTAL CONTROL SUBSYSTEM STUDY

by

Kenneth L. Heitner

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TRW Energy Systems Planning Division
McLean, Virginia 22102

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EXECUTIVE SUMMARY

The purpose of this study is to select the "best" technologies for the environmental control subsystem (ECS) in electric and hybrid vehicles. The "best" technology must be selected from technologies that are available in the near term. The selected technology will serve as a basis on which development of a prototype ECS could start immediately.

The technology selected as "best ECS for the electric vehicle is the combination of a combustion heater and gasoline engine (Otto cycle) driven vapor compression air conditioner. All of the major ECS components, i.e., the combustion heater, the small gasoline engine, and the vapor compression air conditioner are commercially available. These technologies have good cost and performance characteristics. The cost for this "best" ECS is relatively close to the cost of current ECS's. At the same time, its effect on the vehicle's propulsion battery is minimal and the ECS size and weight do not have significant impact on the vehicle's range.

The required technology also minimizes risk for the vehicle manufacturer because little new capital investment will be needed to produce the ECS. Since electric vehicles are likely to be in limited production for several years, the technology is appropriate for the market size.

The "best" ECS for the hybrid vehicle also uses a combustion heater. The vapor compression cooling system can be driven electrically or, if conditions permit, mechanically from the main propulsion system. Again, the main characteristics of this choice are reasonable cost, good performance, and minimal financial risk to the vehicle manufacturer.

In the design of both ECS systems, ventilation loads are reduced by restricting the level of ambient makeup air used in the ECS. Most of the interior air will be recirculated through a charcoal filter bed to provide odor control. Solar radiation loads through the windows will be reduced by use of tinted glass and rear window louvers. Waste heat from the propulsion system will be recovered to minimize fuel consumption in the heating mode. For the hybrid vehicle, waste heat from the heat engine will supply all the heat on longer trips when there is significant heat engine operation.

How the "Best" ECS is Selected

Selection of the "best" ECS is an important part of the vehicle's design because the ECS is an energy intensive subsystem. It must provide heating and cooling of the passenger compartment, defrosting and defogging of the windshield, and temperature control of the battery pack. These services must be provided under extreme climate conditions which place high energy demands on the vehicle's energy sources.

In order to select the "best" ECS, the study is organized into several key steps. First, the functional requirements for the ECS are determined. Next, a rating scheme is devised to evaluate the ECS alternatives. About thirty potential ECS elements are identified. Descriptions and characterizations are prepared for each element to serve as the basis of the evaluation procedure.

The actual evaluation is carried out as a multi-step process. Initially, inappropriate ECS elements are eliminated. Separate heating and cooling elements are combined to produce total ECS's. These are ranked and a "best" ECS selected. Separate evaluations are made for the electric and hybrid vehicles.

Development of the Functional Requirements

Separate functional requirements are developed for each of the following:

- Passenger Compartment Heating and Cooling
- Windshield Defrosting and Defogging
- Battery Temperature Control

Simple steady-state models are developed for calculating each set of loads. The passenger compartment model accounts for conduction, ventilation, solar radiation and interior heat loads. Calculations for the windshield defroster-defogger loads cover the requirements of Federal Motor Vehicle Safety Standard 103, as well as dynamic deicing and defogging conditions. The passenger compartment and defroster loads are used to determine the heating and cooling capacity of the ECS. Battery heating and cooling loads are found to be relatively small, unless rapid battery charging is involved.

One important result from development of the functional requirements is the understanding gained regarding techniques to reduce the ECS loads. Two means of reducing the ECS load are by use of recirculating ventilation system and by limiting the solar radiation load. Reduced ECS loads allow for the use of smaller and less costly ECS elements, reduction of ECS energy requirements, and reduction of ECS impact on vehicle range.

Evaluation Methodology

The evaluation of the alternative ECS technologies depends on the following four major factors:

- The rating score
- The range penalty
- The status of technical development
- Appropriateness for market size

The rating score is devised as an overall quantitative measure of how well each ECS compares to a hypothetical baseline technology. The ideal system will have a rating score of 100, while real systems are somewhat lower. Relative cost is the most important factor in the rating score. Weight, size, and energy use are also utilized in this calculation. Energy use is based on the use of liquid fuels by the ECS.

The range penalty is a measure of how much the vehicle's range will be reduced by the ECS. For the electric vehicle, range penalty reflects the ECS's electrical energy use, size, and weight. For the hybrid vehicle, only energy use is reflected in the range penalty.

Status of technical development is an important criteria in selection of the "best" ECS. Only existing or near-term technologies can be selected for the "best" ECS. Potentially superior technologies available in the mid-term can be recommended for extensive development. Very long-term technologies are not considered.

Finally, the technology selected must be appropriate for the market size. Technologies for vehicles likely to be in limited production, such as near-term electric and hybrid vehicles, should be available from other markets where they are already in large scale production. This reduces the risk and requirements for capital investment by the vehicle manufacturer until the market justifies such an investment.

ECS Elements Considered

A wide range of technologies are considered in the ECS element evaluation. The largest group of ECS elements are those involving energy conversion. This includes direct conversion technologies, i.e., combustion and resistance heaters. It also involves a large number of heat pump cycles, including the more familiar vapor compression and reverse Brayton cycles. The heat pump options also include the less well known Ericsson and hydride cycles. The heat pumps can be driven electrically, by direct heat (e.g., absorption cycle) or by a heat engine (such as the Otto, Stirling or Ericsson cycles).

Energy storage systems are also considered as ECS elements. Energy can be stored thermally for heating or cooling purposes. Energy can also be stored in reversible chemical reactions or in heat of solution.

A variety of other ECS elements are also examined. These include the use of charcoal filters to provide odor control with a recirculating ventilation system. Tinted window films and rear window louvers are also examined as means of providing control of solar radiation inputs.

Elimination of Inappropriate Elements

A number of technologies are simply inappropriate for the vehicle requirements. Some technologies, such as the hydride and jet compression heat pump, require very long development times. Most of the energy storage techniques are either too heavy or too expensive for vehicular applications. For the electric vehicle, none of the ECS's can be electrically operated without range penalties of over 20 percent. Technologies eliminated as inappropriate are not included in the detailed evaluation process.

Evaluation of the "Best" ECS

There are several strong contenders for the "best" ECS in the electric vehicle. Among the contenders is the combination of the combustion heater and the gasoline engine (Otto cycle) driven reverse Brayton cycle (ROVAC). The principle reason for selecting vapor compression over the ROVAC is that vapor compression is already in widespread automotive application. Although the ROVAC is slightly more favorable in terms of cost, the difference is not sufficient to justify a major changeover in technology.

For the hybrid vehicle, ECS's based on the ROVAC cooling cycle are potentially competitive, but not sufficiently attractive to warrant changing to a new technology. However, there are several approaches to driving the cooling system which are essentially equivalent. The direct mechanical drive appears to be the best, assuming there is no negative impact on the main propulsion system. An arrangement could be provided to "declutch" the ECS under conditions of maximum load on the propulsion system.

ECS Prototype Development

The development of a prototype ECS should emphasize three key points. First, the components selected for the ECS must be "qualified" for automotive service. Next, the detailed system design must be integrated so the components work properly in all possible modes of system operation. Finally, the ECS must be extensively tested to make sure it actually meets its operational requirements and market acceptability criteria. It will also be desirable to test the ECS for reliability over the expected vehicle lifetime.

The development process would be done in several stages. Most likely, new designs for the ECS would be prepared for a specific vehicle or vehicle type. A bench test ECS would be constructed and extensively tested in the laboratory environment. When this is completed, a final ECS design would be "repackaged" and the vehicular ECS built. The vehicular ECS would be extensively tested in the vehicle and modified until a satisfactory design was obtained.

Since the electric and hybrid vehicle ECS's are very similar, it would be best to concentrate on the electric vehicle ECS development. The existing electric vehicle market is growing and is likely to remaind larger then the hybrid vehicle market for the next several years. Most of the hybrid vehicle ECS features, such as the recirculating ventilation system and control of solar inputs, could be integrated into the current hybrid vehicles ECS design. The current (Phase II) hybrid vehicle design already has provisions for a combustion heater and a mechanically driven vapor compression cycle air conditioner. (See Reference 9-2).

The ECS prototype is estimated to require about a year to develop. The basic labor costs for the development will be about $250,000. Additional costs for components, materials, and test facilities are not estimated but potentially can add significantly to the total program costs.

More Extensive Prototype Development

Certain technologies potentially offer ECS designs that would be more efficient, as well as smaller and lighter. Based on the data available to this study, the Ericsson Ericsson and Electric Ericsson cycles, under development by Energy Research and Generation appear to be the most attractive. However, because of the uncertainty surrounding vehicle technology from factors such as:

- Improvements in battery technology
- Future fuel and electricity prices
- Relative market penetration of electric and hybrid vehicles,

a specific program of technical development cannot be recommended. Research efforts should be focused on obtaining detailed characterizations of attractive advanced heat pump technologies. Data from such characterizations would allow clearer decisions to be made about specific product developments utilizing these technologies at a future date.

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1.0 INTRODUCTION

1.1 PURPOSE

The purpose of this report is to provide a complete summary of the Electric and Hybrid Vehicle Environmental Control Subsystem Study. The intention is for this document to provide complete documentation of the study. However, occasional reference to the interim reports of this study may be required (References 1-1, 1-2, 1-3, and 1-4).

1.2 SCOPE

To achieve these goals, the report provides complete coverage of all ten tasks described in the statement of work (Reference 1-5). An overview of the main tasks of the project is given in Figure 1-1. The main elements of the project are as described in the following paragraphs.

In Task 1, the functional requirements for the environmental control subsystem (ECS) are developed. This information is used in Task 2 where a rating scheme is developed to evaluate the candidate technologies. The list of candidates is generated in Task 3 and specific information about each candidate is developed in Task 4. Candidates which are clearly inappropriate to meet the functional requirements are eliminated in Task 5. The remaining elements for the electric vehicle are ranked in Task 6. The "best" ECS for the electric vehicle is selected in Task 7. Task 8 covers the special requirements to cool the battery pack. A separate evaluation of ECS alternatives was made for the hybrid vehicle in Task 9. Estimates for ECS prototype development were made in Task 10. This report is part of Task 11.

The major data sets collected during these tasks, as well as the models and evaluation procedures developed, are summarized in this report. It includes separate findings on the "best" ECS for electric and hybrid vehicles. Recommendations are also made for future work in developing these ECS's, with estimates of the resources required.

1.3 ORGANIZATION OF THE REPORT

The remainder of the report is organized essential by the task outline. The only difference is that Tasks 3 and 4, as well as Tasks 6 and 7, have been combined into single sections. Parallel methods were followed in the selection of the electric and hybrid vehicle ECS's. Table 1-1 gives the correspondence between tasks and sections of the report. A general summary has been added in Section 10.

Table 1-1. Correspondence Between Task Numbers and Report Sections

Task Numbers	Task Titles	Report Section
1	Development of Functional Requirements	2.0
2	Development of Rating Scheme	3.0
3 & 4	Identification and Description of ECS Elements	4.0
5	Elimination of Inappropriate Elements	5.0
6 & 7	Ranking of ECS Elements and Identification of the "Best" ECS	6.0
8	Impact of Battery Cooling ECS	7.0
9	"Best" ECS Reassessment for Hybrid Vehicle	8.0
10	Estimates for ECS Prototype Development	9.0
11	Documentation and Final Briefing	All Sections including 10.0

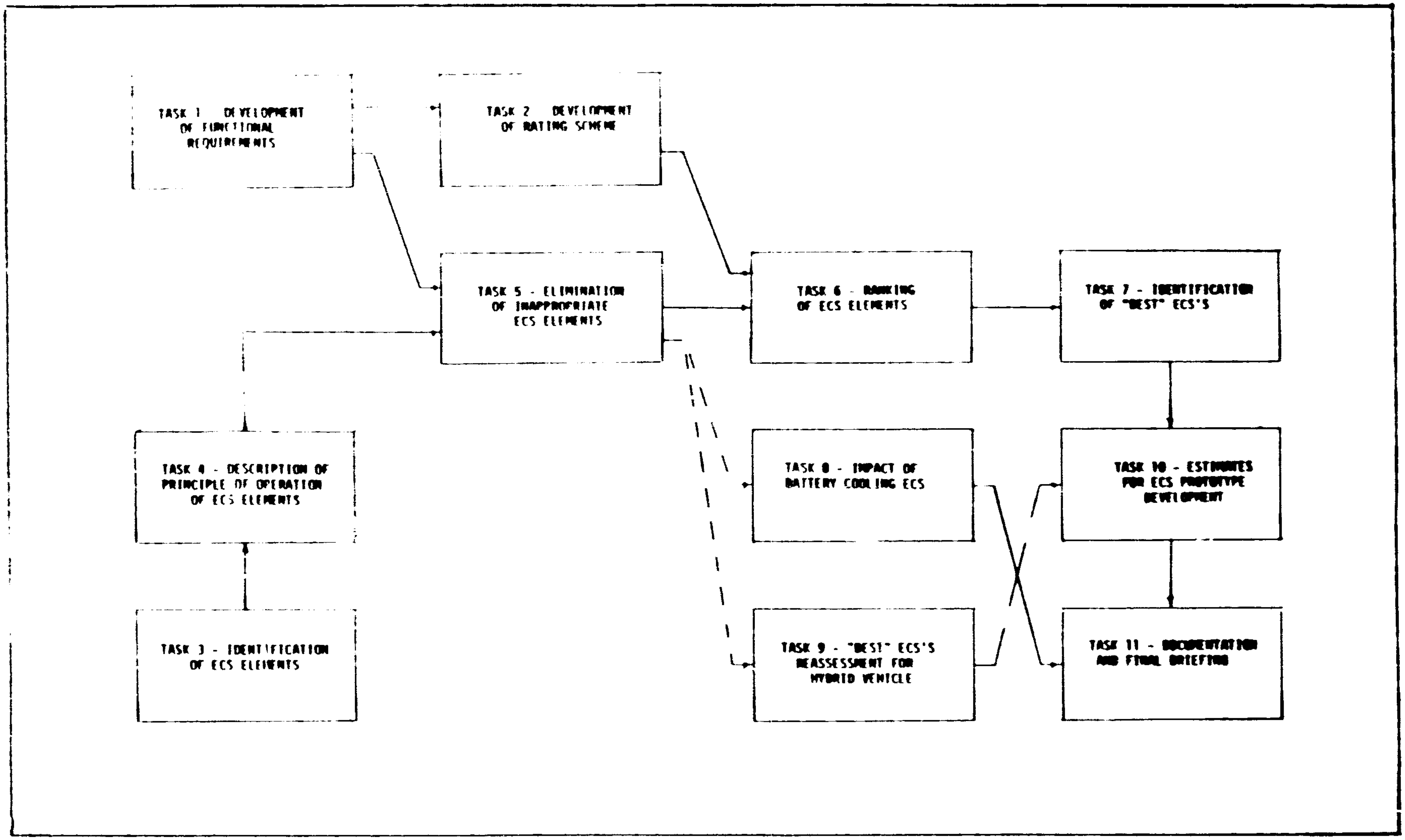


FIGURE 1-1. OVERVIEW OF PROJECT ORGANIZATION - ELECTRIC AND HYBRID VEHICLE ENVIRONMENTAL CONTROL SUBSYSTEM STUDY

2.0 DEVELOPMENT OF FUNCTIONAL REQUIREMENTS

2.1 METHODOLOGY

The functional requirements for the environmental control subsystem (ECS) arise from three sources. First, the vehicle's use patterns determine how often the ECS will be required to operate and for how long a period. The range of climate conditions encountered determine the capacity requirements for the ECS to provide passenger comfort under extreme conditions. These factors need to be combined with physical models of the vehicle and vehicle systems to determine the functional requirements for the ECS on a sound engineering basis. This section of the report discusses the methodology for development of the functional requirements.

2.1.1 Development of Trip Scenarios

The main characteristics of vehicle trips that affect ECS operation are trip time and daily frequency. However, in studying vehicle use patterns, the data is often given in terms of trip length. Thus, vehicle speed must also be determined in order to calculate trip time.

The most comprehensive source of data on personal transportation use is the Nationwide Personal Transportation Study (Reference 2-1). This study was designed to obtain up-to-date information on national patterns of travel from 1970 Census data. Although the data is indicative of behavior before the energy price increases of 1973, the results are likley to be conservative. That is, today's vehicle trips are shorter and less frequent because of motorist's desire to save fuel.

Work and Shopping Trips

Table 2-1 summarizes the key characteristics of work and shopping trips. To characterize shopping, it is probably better to use the broader category "family business" which includes shopping trips as a subset. The results of Table 2-1 show that over 50% of all vehicle miles are trips of relatively short duration. Naturally, this average data must be used with some caution since the distributions of trip length and time are rather broad.

Table 2-1. Characteristics of Major Auto Trip Types

Trip Characteristic	Work*	Trip Type Shopping	Family Business
Average Length (km)	15.0	7.1	9.0
(mi)	9.3	4.4	5.6
Average Speed (kph)	38.5	29.0	29.0
(mph)	23.9	18	18
Average Duration (Min)	23.3	14.7	18.7
Frequency (per day)	2**	0.5	1
Percentage of Vehicle Miles	33.7	7.5	19.3

*Home to work and work to home.

**90 percent are Monday through Friday.

Source: Reference 2-1 Report #10
Tables 9 and 10

The implication of these short trip times is that ECS must respond quickly to be effective. On the other hand, vehicle use is basically infrequent; that is, most of the time the vehicle is parked at rest.

Trip Simulation

For purposes of evaluating and testing vehicle behavior, it is useful to characterize these trips in terms of the standard driving cycles. For the electric and hybrid vehicles, the characteristics of the Jet Propulsion Laboratory (JPL) modified Society of Automotive Engineers (SAE) "D" cycle are appropriate.

These characteristics are on a per cycle basis:

Distance	-	1.57 km	(0.977 miles)
Duration	-	122 seconds	
Average Speed	-	46.4 kph	(28.8 mph)

Thus, the work trip can be represented by 9 or 10 "D" cycles, and the family business trip by 5 or 6 cycles. The lower average speed during the trip could be simulated by adding longer pauses between the individual cycle runs.

Maximum Range Scenario

Occasionally, a vehicle has to make a very long trip. For the electric vehicle, this trip length is limited by the battery storage system to about 105 km (65 miles) or 66 "D" cycles. However, such trips represent only one percent of all trips (Reference 2-2), and therefore are rather infrequent. Such a trip would have a duration of about 2.2 hours.

The hybrid vehicle, by contrast, can operate for much longer periods of up to 10 hours. The implications of this ECS design are discussed in Section 8.0.

2.1.2 Climate Conditions

The thermal criteria for this study are based on the JPL Guidelines (Reference 1-5). These guidelines suggest the following design temperatures:

Winter:	-29°C	(-20°F)	
Summer:	49°C	(120°F)	Dry Bulb

Comparing these conditions with winter and summer design conditions given by ASHRAE (Reference 2-3) for extreme climates in the continental United States, these conditions seemed reasonable. (For the summer conditions, the appropriate wet bulb temperature was taken to be 29°C (85°F).)

However, it should be pointed out that automotive systems are general designed for more relaxed conditions. Heating systems are designed for -18°C (0°F) (References 2-4 and 2-5). Cooling systems are typically designed for 38°C (100°F-dry bulb), 26°C (78°F-wet bulb) (References 2-4, 2-6, 2-7).

Solar Radiation Loads

Solar radiation input through the vehicle's windows varies with:
- Latitude
- Time of day
- Time of year
- Local atmospheric conditions
- Vehicle design
- Vehicle orientation

At any given instant, however, the solar radiation is an unknown component which can contribute to the ECS requirements. System designs are based on the maximum radiation levels that are encountered. Hence, it is sufficient to know that the maximum solar input anywhere in the United States is about 946 watt/m^2 (300 Btu/ft^2 -hr) (Reference 2-8).

2.1.3 Overview of Development of Functional Requirements

The approach to developing the ECS functional requirements is broken down into three separate requirements. These requirements are:

- Passenger Compartment Heating and Cooling
- Windshield Defrosting and Defogging
- Battery Environmental Control System

The second item includes the requirement to meet Federal Motor Vehicle Safety Standard (FMVSS) 103.

Passenger Compartment Heating and Cooling

The approach used to develop the functional requirements for the passenger heating and cooling systems is given in Figure 2-1. The key elements of the approach are as follows:

1. Performance of current vehicle heating and cooling systems will be characterized from reported test data.

2. A simple vehicle heat loss model will be developed accounting for conductive, convective, and radiative heat transfer. The loss model will be utilized to estimate vehicle heating and cooling requirements for the extreme climatic conditions, different ventilation levels, and passenger loads. The analysis assumes a favorable management of the solar input and ventilation loads.

3. Trip scenarios for work and shopping will be constructed from basic vehicle use pattern data. The time required to reach steady temperature will be characterized in terms of performance of current heating and cooling systems, as well as fraction of trip time. Requirements for system capacity under the maximum range (66 "D" cycles) scenario will also be investigated.

Windshield Defrosting and Defogging

Three separate requirements for heating the windshield are examined. These requirements include:

- The Federal Motor Vehicle Safety Standard 103 Test
- Dynamic Deiceing
- Dynamic Defogging

The heat requirements are calculated for a heater embedded in the windshield, as well as a moving air stream defroster. The maximum load from these three requirements will determine the defroster's capacity.

Battery Environmental Control System

A general approach to developing the requirements for the battery environmental control system is outlined in Figure 2-2. The key elements of this approach include the following:

1. An allowable temperature range for the battery will be determined from the JPL Guidelines (as revised in Reference 2-9).

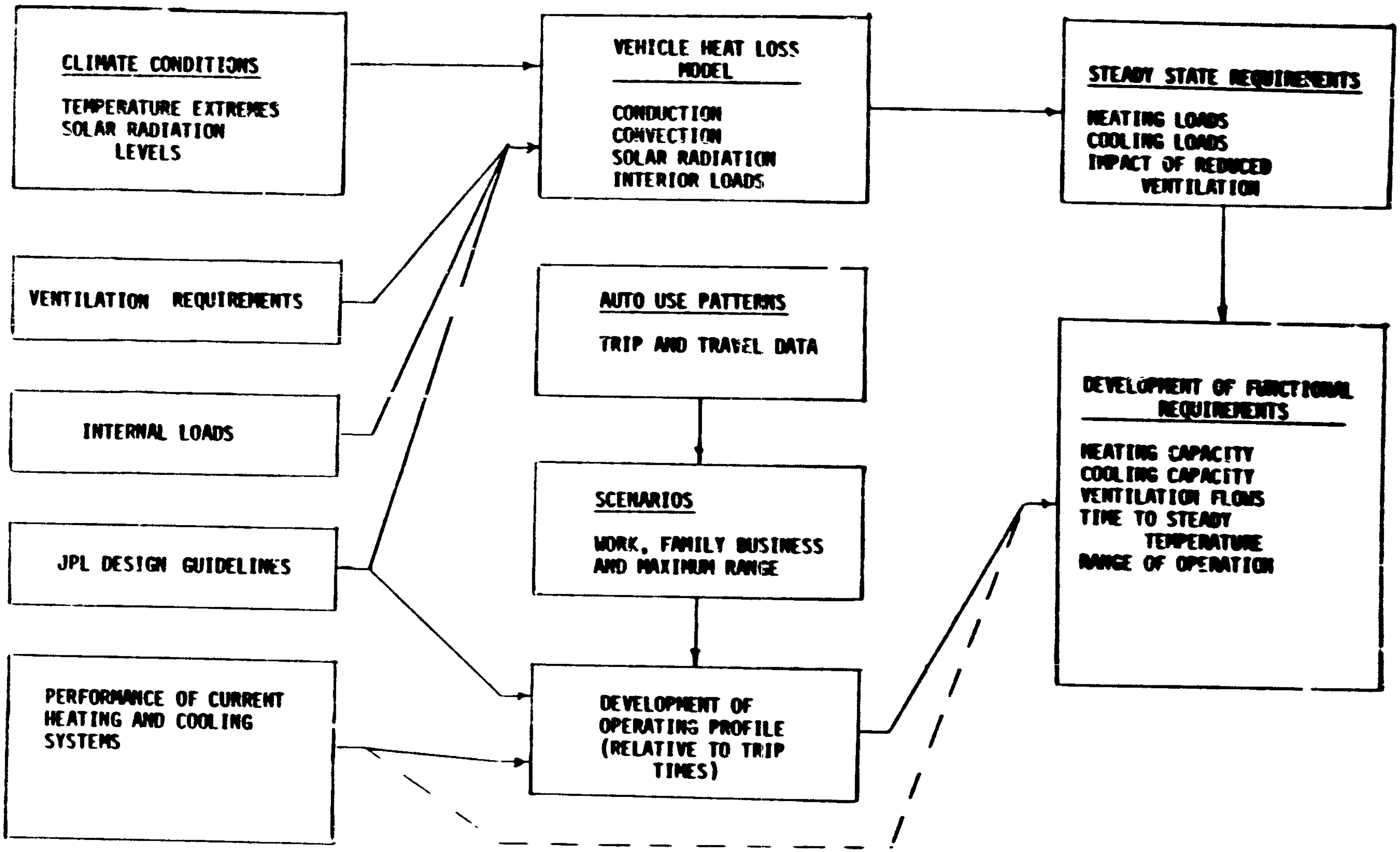


Figure 2-1. Development of Functional Requirements For Passenger Compartment Heating and Cooling

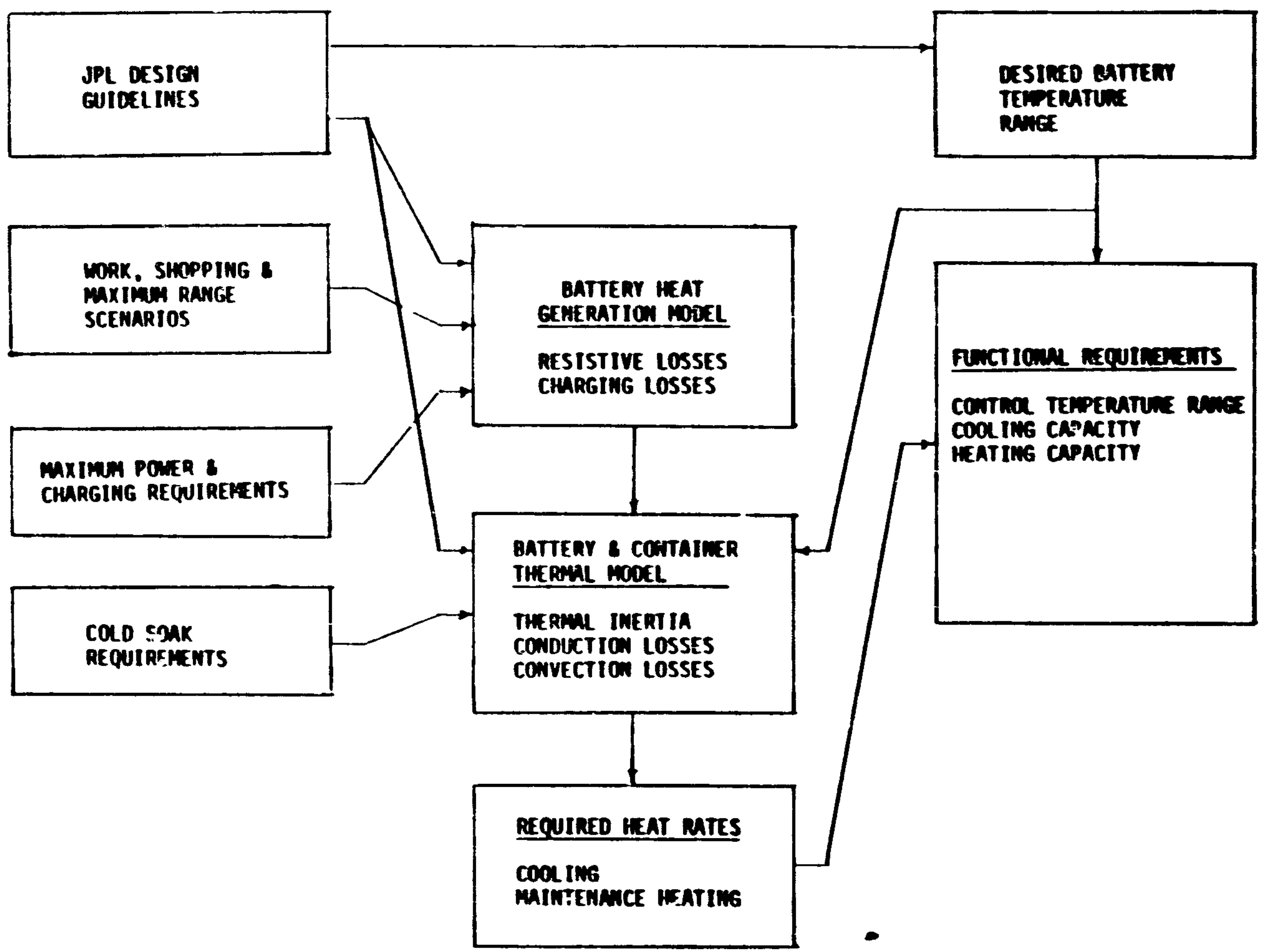


Figure 2-2. Development for Functional Requirements For Battery Environmental Control System

2. A battery thermal model and a battery heat loss model will be developed. Battery heat evolution will be studied for a variety of operating modes including:

   - Charging
   - Work, family business and maximum range trips
   - Hill climbing (maximum power)
   - Cold soak

3. Functional requirements for heating and cooling the battery will be determined for the worst heat loss mode. The heating and cooling system will maintain the battery pack in the desired temperature range.

2.2 PASSENGER COMPARTMENT HEATING AND COOLING

2.2.1 Vehicle Heat Loss Model

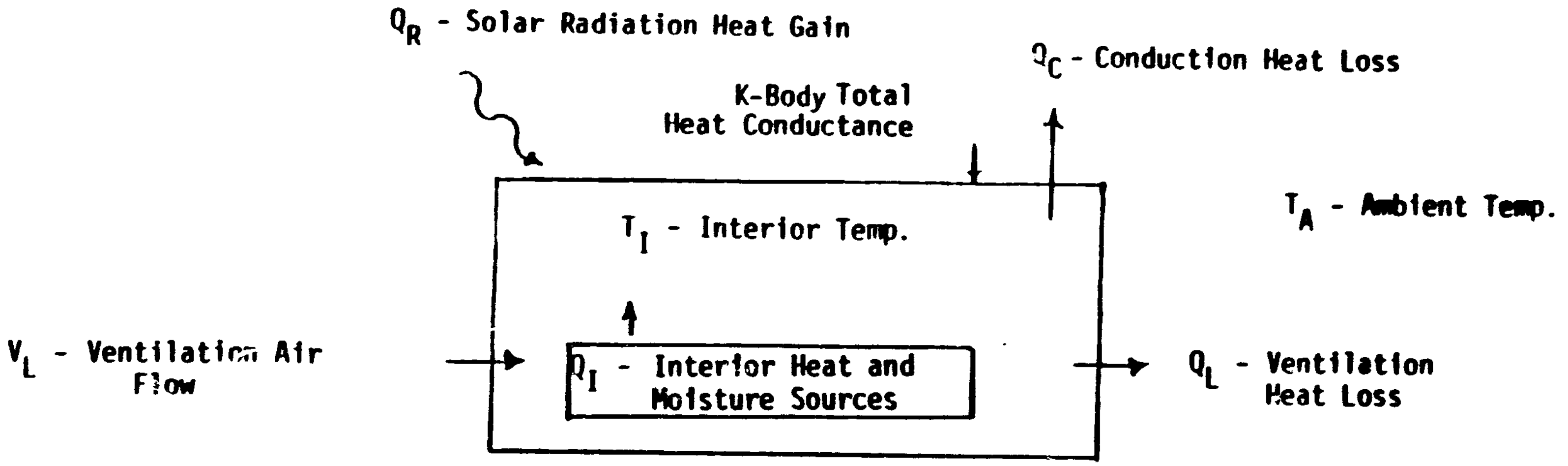
The vehicle's requirements for heating and cooling can be defined in terms of a simple model for the vehicle's heat losses and gains shown in Figure 2-3. The heating and cooling system must supply or remove the heat needed to balance the other system inputs in steady state operation. The main terms in the heat balance are:

- Conduction
- Convection
- Solar Radiation
- Interior Heat and Moisture Sources

Model parameters will be used for subcompact, four passenger vehicles that are similar to the prototype electric vehicles being developed in the DOE Near Term Electric Vehicle Program.

Conduction

Heat is transferred to or from the passenger compartment by the vehicle's structure, including the body panels and window glass. Reference 2-10 reports of an experimental technique of measuring the heat transfer coefficient by means of wind tunnel tests in which the vehicle is treated as a heat exchanger. The overall heat transfer coefficient is found to be a function of both vehicle velocity and internal infiltration ventilation air flow. A typical value of body conductance for a small vehicle was taken to be 40 watts/°C (21.1 Btu/hr-F°), based on the data in References 1-1 and 2-10.



$$Q_C = K\,(T_I - T_A)$$

$$Q_L = \rho V_L\, C_p\, (T_I - T_A)$$

For Heating $Q_{ECS} = Q_C + Q_L - Q_I$

For Cooling $Q_{ECS} = Q_I + Q_R - Q_C - Q_L$

ρ - Air Density

C_p - Specific Heat of Air

Figure 2-3. Basic Vehicle Heat Loss Model

Convection

Outside air is normally brought into the vehicle through the ventilation system to ensure fresh air for the passengers and minimize the potential build-up of carbon monoxide in the vehicle compartment. Because the natural ventilation rate is low, a supplementary fan is usually added. The fan increases ventilation air flow at low speeds.

Reduced ventilation air flow is acceptable in electric vehicles, because there is less concern about buildup of exhaust fumes in the passenger compartment. However, other requirements such as odor control need to be considered. For vehicle operation with 4 passengers, 255 m^3/hr (150 cfm) of ventilation air is needed to provide adequate odor control. (References 1-1 and 2-3.)

Preliminary calculations show that allowing this high ventilation level results in large heating and cooling loads. A desirable approach would be to achieve odor control by other means such as recirculating the air flow through a charcoal filter (see Section 4.4). Thus, the total ventilation flow (make-up air) would only be about 43 to 77 m^3/hr (25 to 45 cfm), for adequate ventilation. This would require changes from current ventilation system design practice.

Solar Radiation

As discussed earlier, incident solar radiation on a horizontal surface can reach peak values of 946 watt/m^2 (300 Btu/ft^2-hr). To reduce this heat load, shaded or tinted glass is used. Tinted glass only transmits 62% to 68% of the radiant heat (References 2-11 and 2-12). Also, the rear window is assumed to be covered with horizontal louvers which are estimated to reduce the heat transmission to 25% or less.

The solar radiation load was calculated on the basis of the projected glass area in plan view (sun directly overhead). The DOE near-term electric vehicle developed by Garrett (Reference 2-13) has a projected glass area of 2.56 m^2 (27.6 ft^2) which was taken as a typical design example; 0.83 m^2 (8.9 ft^2) of this area is in the rear window.

Hence, for this vehicle, the estimated solar radiation load is 1941 watts (6624 Btu/hr). This could be reduced to 1011 watts (3451 Btu/hr) by the use of tinted glass (65% transmission) and rear window louvers (25%

transmission). This estimate is approximate. It does not fully account for diffuse sky radiation or ground reflection as additional potential heat inputs.

Interior Heat Sources

The vehicle interior has two principal heat sources: its occupants and auxiliary equipment, such as ventilation fans, operating in the vehicle's interior. Heat gain from occupants is tabulated in Reference 2-3 and shown in Table 2-2. Heating and cooling loads were based on maximum vehicle occupancy of four persons. An accessary heat load of 146 watts (500 Btu/hr) was assumed for interior electrical equipment.

2.2.2 Steady State Heating and Cooling Loads

The purpose of the vehicle's heating and cooling system is to make the passengers comfortable. Extensive studies of comfort (Reference 2-3) show that a sedentary lightly clothed person is comfortable in a temperature range of approximately 22 to 25°C (72-77°F) and 20 to 60% relative humidity. However, the comfort temperature will decrease with heavier clothing, and increase with increasing air velocity surrounding the person. The somewhat more active vehicle driver, if also more heavily clothed, may be comfortable at much lower temperatures. Thus, the heating requirement was based on 18°C (65°F) steady state temperature.

Experimental tests (Reference 2-14) in a simulated vehicle environment indicate that people will report having achieved "comfort" at interior temperatures as high as 35 to 38°C (95-100°F). This is because their upper torso and face are subjected directly to the ventilation jet from the air conditioner. This effect can allow the vehicle occupants to achieve comfort in a fraction of the time required to reach comfortable temperatures throughout the vehicle interior.

For purposes of this analysis, the steady state air conditioning capacity was calculated. Capacity was calcualted for an equilibrium interior condition of 25°C (77°F) and 40% relative humidity (RH). However, this is done with the realization that passenger comfort can potentially be achieved at higher average temperatures.

Table 2-2. Total Heat Gain from Vehicle Occupants[+]

Activity of Occupant	Total Adjusted[*] Heat Load (watts)	(Btu/hr)
Driver (Moderately Active-Seated)	149	(510)
Passenger (At Rest-Seated)	100	(340)

[+]Total heat includes sensible and latent heat.

[*]Adjusted for a mix of men, women, and children.

Source: Reference 2-3

Tables 2-3 and 2-4 summarize the steady state requirements for the heating and cooling system as derived from the vehicle heat loss model. For purposes of heat transfer calculations all air flows are assumed to be at 15°C (59°F) and standard atmospheric pressure of 101 kN/m^2 (14.7 psia). The specific volume of air is 0.82 m^3/kg (13.1 ft^3/lb). The specific heat of air at constant pressure is 4.17 kJ/kg-°C (0.24 Btu/lbm-°F).

It is clear from this model that there is an important trade-off between steady state requirements for heating and cooling and ventilation flows. In general, under extreme heating or cooling loads, it is highly desirable to minimize ventilation flows by use of a recirculating air system. Figures 2-4 and 2-5 show how the heating and cooling loads are reduced when a recirculating air system is used. The ventilation rates of 43 to 77 m^3/hr (25 to 45 cfm), are considered to be appropriate for determining the design capacities of the electric and hybrid vehicle ECS.

In new vehicle designs, other inputs such as solar radiation should also be managed effectively. Attention should be given to minimizing glass area, particularly the plan view area, to minimize steady state cooling loads.

A Comparison with Performance of Current Heating and Cooling Systems

Heating and cooling systems in current vehicles have usually been generously sized. Heating systems typically provide capacities of up to 7.3 kW (25,000 Btu/hr) (Reference 2-7). Since very large amounts of waste heat are available from the engine cooling jacket, extra capacity is easily obtained.

Tests on heater defroster systems in current vehicles show that most vehicles reach full heat capacity in about 10 minutes from an -18°C (0°F) cold start. Typical systems have outlet temperatures of about 59°C (135°F).

Cooling systems with capacities from 5.3 to 7.0 kW (18,000 to 24,000 Btu/hr) are typical of those found in U.S. cars (Reference 2-6 and 2-7). Smaller vehicles have slightly lower cooling requirements, but system capacities are often restrained more by space requirements than other considerations.

Table 2-3. Calculation of Steady State Heating Requirements (For 4 Passengers)

Goal

$T_I = 18°C\ (65°F)$ at $T_A = -29°C\ (-20°F)$

Conduction

$Q_C = K\ (T_I - T_A)$

$K = 40$ watts/°C (21.1 Btu/hr-°F)

$Q_C = 1887$ watts (6441 Btu/hr)

Infiltration

$Q_L = V_L\ C\ (T_I - T_A)$

$V_L = 255\ m^3/hr$ (150 cfm-Full ventilation load for 4 passengers)

$C = 5.08\ kJ/m^3$-°C ($0.0183\ Btu/ft^3$-°F)

$Q_L = 4103$ watts (14000 Btu/hr)

Solar Radiation

Assumed = 0

Interior (Passenger)

Driver & 3 Passengers = -448 watts (-1530 Btu/hr)

Total

$Q_T = 5542$ watts (18911 Btu/hr)

(This could be reduced if 147 watts (500 Btu/hr) of interior loads from electrical equipment were credited.)

Table 2-4. Calculation of Steady State Cooling Requirements (For 4 Passengers)

Goal

T_I = (25°C) (77°F-RH = 40%) at T_A = 49°C (120°F) $T_{wet\ bulb}$ = 29°C (85°F)

Conduction

$Q_C = K\,(T_I - T_A)$

K = 40 watts/°C (21.1 Btu/hr-°F)

Q_C = 955 watts (3258 Btu/hr)

Infiltration

$Q_L = V_L\,\Delta H$

V_L = 255 m^3/hr (150 cfm-Full ventilation load for 4 Passengers)

ΔH = (Enthalpy change of air-water mixture - Enthalpy of condensed water vapor)/Specific volume of dry air.

Enthalpy change of air-water mixture = 55.7 kJ/kg (24 Btu/lb) of dry air

Enthalpy of condensed water vapor = 0.56 kJ/kg (0.24 Btu/lb) of dry air

Specific volume = 0.82 m^3/kg (13.1 ft^3/lb) of dry air at 15°C (59°F)

ΔH = 67.4 kJ/m^3 (1.81 Btu/ft^3)

Q_L = 4774 watts (16290 Btu/hr)

Solar Radiation

Q_R = (from Section 2.21) 1011 watts (3451 Btu/hr)

Interior (Passengers and Auxiliary Equipment)

Q_I = (Driver, 3 Passengers, and auxiliaries) = 595 watts (2030 Btu/hr)

Total

Q_T = 7336 watts (25029 Btu/hr)

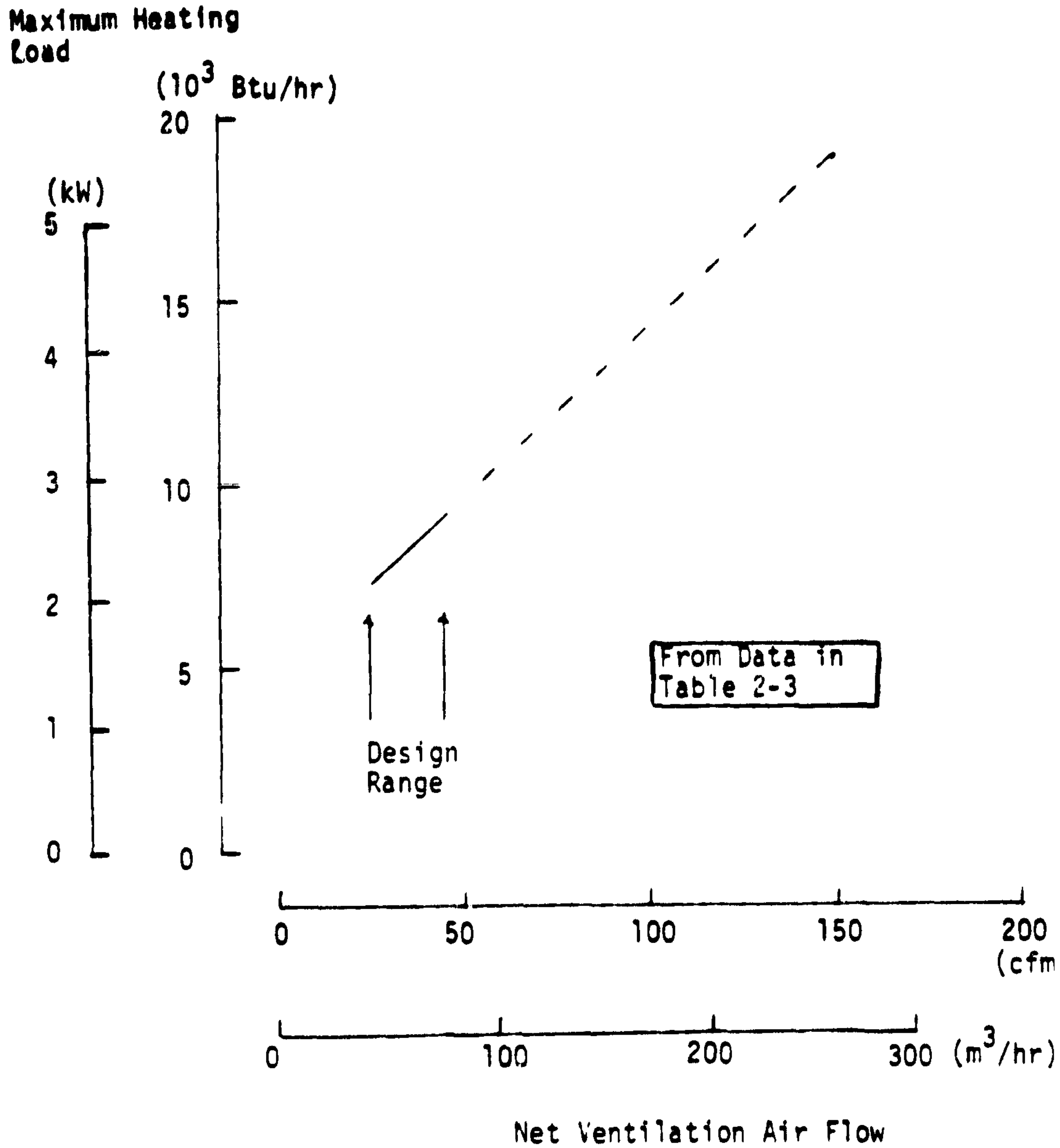


Figure 2-4. Variation in Maximum Heating Load with Ventilation Air Flow

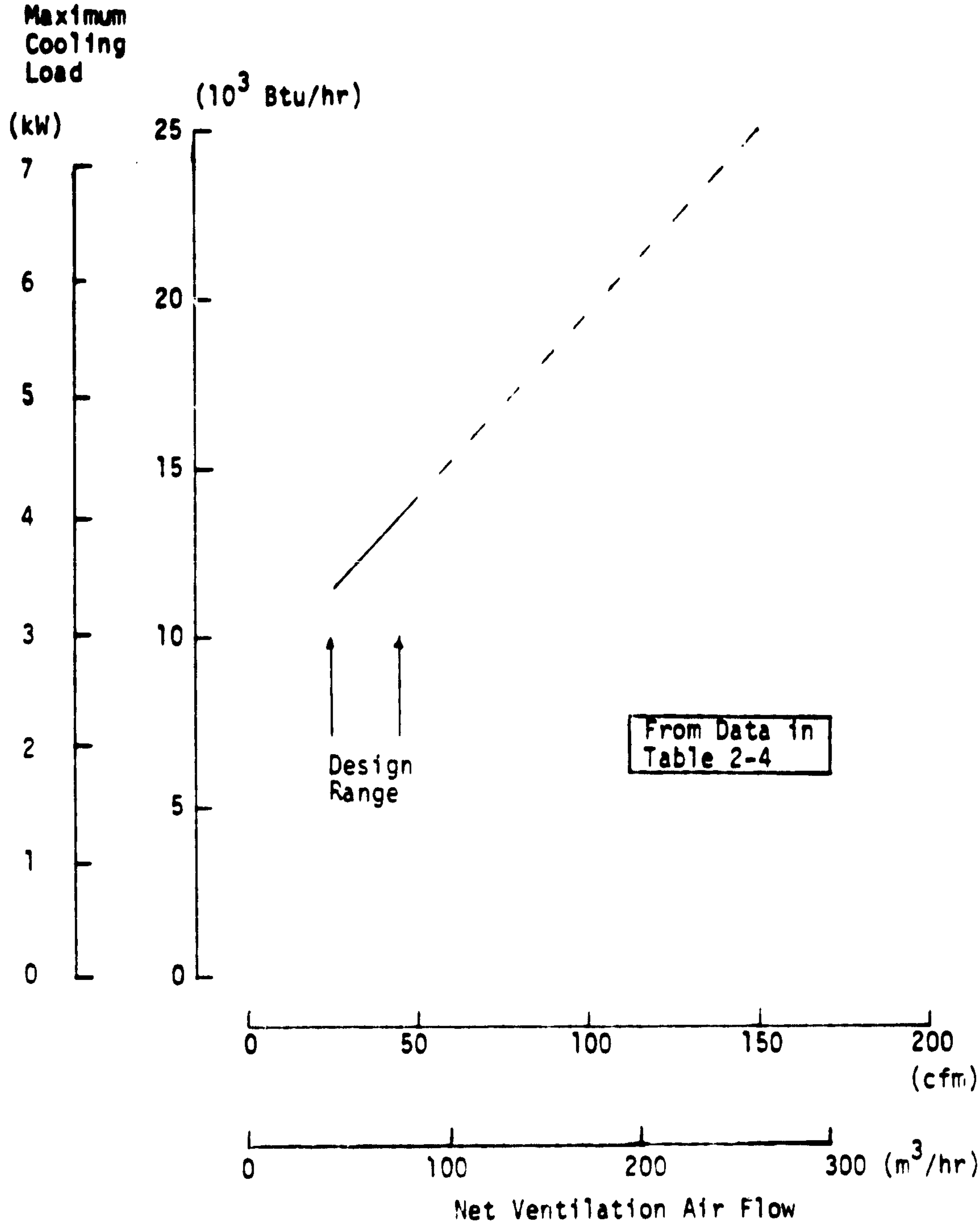


Figure 2-5. Variation in Maximum Cooling Load with Ventilation Air Flow

Cool down response times for automotive air conditioners are not determined by any standard test procedure. In the heating system, the response time is largely governed by the large thermal inertia of the engine and its cooling system. The air conditioner thermal inertia by contrast, only involves a few pounds of refrigerant and the evaporator core. Thus, the air conditioning system itself probably reaches full capacity in one minute or less.

However, the response of the entire vehicle system to cooling is much slower. This is because temperatures in a vehicle soaked in simulated sunlight conditions can easily reach 60°C (140°F) (Reference 2-14). The time to achieve an equilibrium temperature can vary from 10 to 30 minutes (References 2-4, 2-6, and 2-14), depending on initial and ambient temperature and insolation conditions. As noted earlier, passenger comfort will likely be achieved before the vehicle interior has reached equilibrium because the passengers are subjected to the jets of cool air from the air conditioner.

2.2.3 Operating Profiles

Figure 2-6 shows a comparison of current vehicle ECS response time is sufficiently rapid that full heating is available for at least half of a typical trip. The air conditioner response time is longer and full cooling may not be achieved throughout the vehicle during the trip. However, the front seat passengers will achieve comfort in a shorter period, by virtue of directly receiving the cool jets of air from the air conditioner. For longer trips, all systems achieve full conditioning of the passenger compartment.

The performance of current ECS systems can set the standards for the operating profiles of new ECS systems. A new ECS should be capable of delivering the full heating capacity in 10 minutes. The air conditioner should be able to provide comfort to the front seat passengers in the same time period. This can be done if the system essentially reaches full steady state capacity in less than 3 minutes after startup. The air conditioner should essentially achieve equilibrium in 30 minutes.

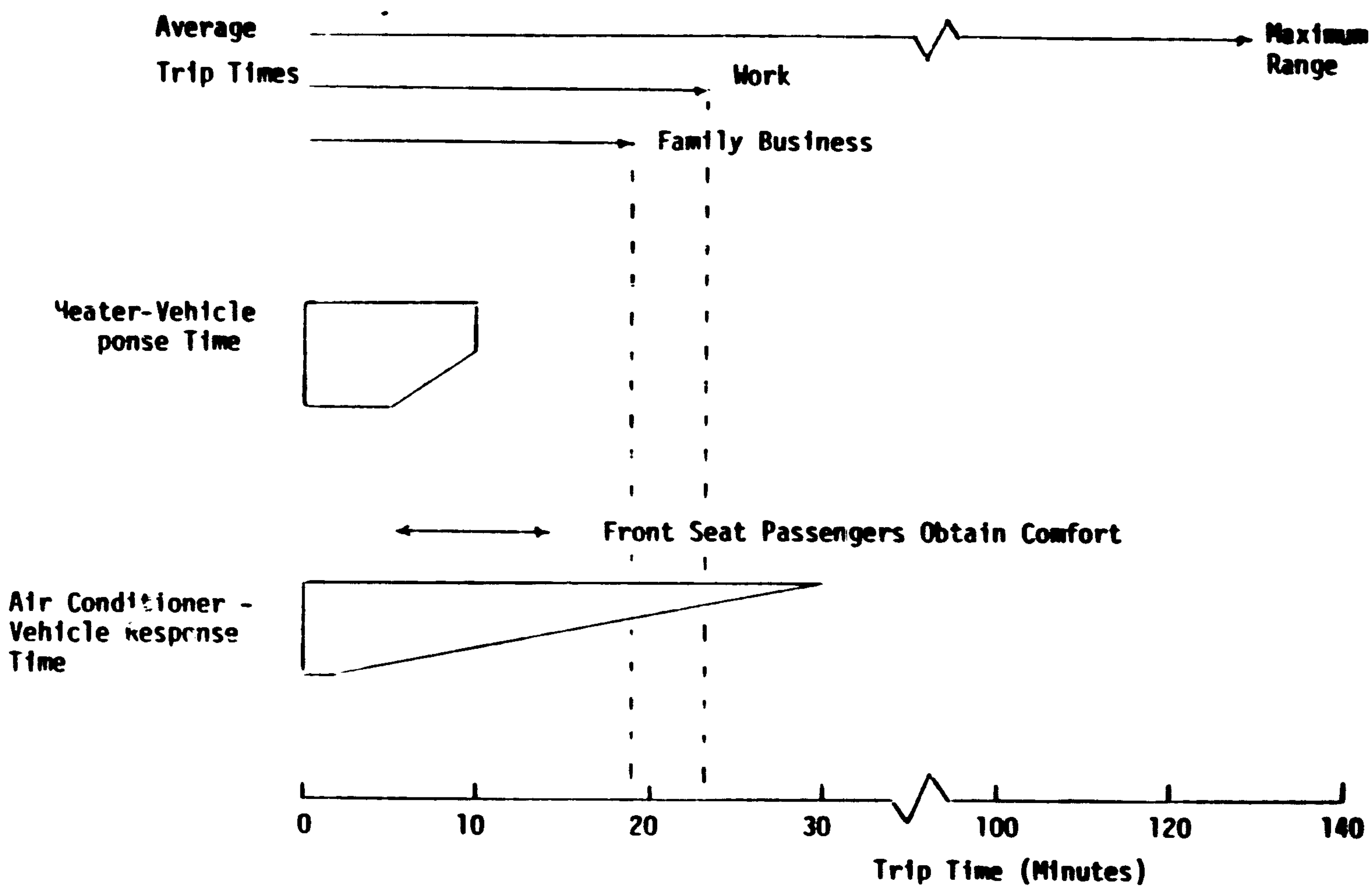


Figure 2-6. Comparison of Current Vehicle ECS Response Times with Average Trip Times

A Comment on Vehicle Thermal Dynamics

No formal models of vehicle dynamic thermal behavior were found in the literature surveyed. All design work cited in the literature is based on equilibrium calculations. For conventional heating system design, the key dynamic element in the response is the thermal warmup cycle of the engine and cooling system. Response of the vehicle interior to the increasing temperature provided by the heater is rapid because virtually all of the infiltration air flows through the heater case. Hence, the heater essentially supplies full capacity as soon as the core has reached the operating temperature.

Cooling system response is potentially more complex to analyze. First, the initial conditions are not well defined. Internal temperatures may be extremely high at the start. Most systems recirculate most or all of the interior air in the initial cooldown in order to rapidly bring the vehicle interior to a lower temperature. However, no models or direct experimental measurements about this process are reported in the literature.

Only static design considerations are used as a basis for the ECS heating and cooling functional requirements because there is no data for dynamic models. Dynamic considerations or requirements will only be expressed in terms which do not require dynamic thermal models.

2.2.4 Discussion of Functional Requirements

The functional requirements for the vehicle passenger compartment heating and cooling are summarized in Table 2-5. Where different requirements were needed to satisfy different conditions, only the more stringent requirements were listed. The basic assumptions behind the requirements are also summarized.

In general, these design requirements are conservative because vehicles rarely operate at these extreme temperatures. The key factor in realizing the design levels is control of the ventilation air to 43 to 77 m^3/hr (25 to 45 cfm), with appropriate provision for odor control.

Undesired solar loads and thermal loads can also be reduced by improving the vehicle's thermal envelope. Tall vehicles, with more vertical windows, will have lower thermal loads in the summer (overhead)

Table 2-5. Functional Requirements for Heater* and Air Conditioner

Heater

1. Capable of maintaining a temperature of at least 18°C (65°F) in passenger compartment at -29°C (-20°F) ambient.

2. Heating capacity 5.7 kW (19,000 Btu/hr) with full ventilation load. Design range is 2.2 to 2.8 kW (7,500 to 9,500 Btu/hr) with controlled ventilation levels.

3. Time to reach capacity is less than 10 minutes.

Air Conditioner

1. Capable of maintaining a temperature of at most 25°C (77°F-RH 40%) in passenger compartment at 49°C (120°F) (29°C (85°F) wet bulb) ambient.

2. Cooling capacity 7.5 kw (25,000 Btu/hr) with full ventilation load. Design range is 3.2 to 4.1 kW (11,000 to 14,000 Btu/hr) with controlled ventilation levels.

3. Time to reach capacity is less than 3 minutes.

4. Time to produce comfort for front seat passengers is 10 minutes.

General Requirements

1. Capable of withstanding mechanical, thermal, vibrational and acceleration environment of electric or hybrid vehicles.

2. System completely sealed and designed so combustion air and exhaust products do not enter passenger compartment.

3. Minimizes use of hazardous materials which could be released in normal opertion or accidents.

4. Capable of being packaged and integrated into the vehicle system.

*Defrosting and defogging requirements are discussed in Section 2.3.

sun. However, this compromises low aerodynamic drag, which is also desirable for efficient electric and hybrid vehicles. Some thermal insulation could be added by foaming door and body panels, or use of fiberglass components, but detailed examination of this option is beyond the scope of this study. Design requirements could also be modified by relaxing the range of climate conditions in which the vehicle is expected to operate. If exterior conditions for the air conditioner are relaxed to 38°C (100°F-dry bulb), then the maximum heat load is reduced by about one third.

Real systems, especially heaters, generally have considerable excess capacity. Building an extra capacity margin into these system designs could be considered, if the penalties on vehicle cost and range are not severe.

Design criteria should also ensure that the technology chosen is suitable for the electric and hybrid vehicle environment and does not introduce exhaust fumes or other hazards into the passenger compartment. Table 2-5 reflects these criteria.

2.3 WINDSHIELD DEFROSTING AND DEFOGGING

2.3.1 Federal Motor Vehicle Safety Standard 103

Discussion of the Standard

Federal Motor Vehicle Safety Standard 103 requires all vehicles to have a windshield defrosting and defogging system(Reference 2-5). The standard outlines a detailed test for each vehicle, which is the basis of determining if the vehicle's defrosting and defogging system is adequate.

The basic nature of the FMVSS 103 test is simple. The vehicle is "cold soaked" at approximately -18°C (0°F). The windshield is coated with a thin layer of ice, about 0.44 kg/m^2 (0.01 oz/in^2). The engine is started and the defroster system blower is operated at maximum flow capacity. The vehicle remains at rest during the entire test period. The defroster is required to clear specified portions of the windshield with a 30 minute period after the engine starts. The areas of the windshield to be cleared are defined in terms of the driver's field of view, and designed to ensure him good visibility of the road ahead.

For purposes of this study, two approaches will be provided to the FMVSS 103 standard. First, the energy required to heat the window and ice film to a point where the ice melts will be estimated. This energy would correspond roughly to the energy a heater embedded in the windshield would need to deliver to satisfy FMVSS 103. A second estimate will be made for energy required to heat an air stream adjacent to the windshield to provide the same heating effect to the windshield and ice film.

Performance Calculation to Meet FMVSS 103

The FMVSS requirement can be analyzed in terms of the actual energy required to heat the windshield and melt the ice. This calculation is summarized in Table 2-6 and would be appropriate for an embedded heater such as an electric resistance system. The appropriate energy requirements appear to be 283 watt-hrs. total in the window. This agrees closely with experimental results for defrosting using electroconducting metal films as embedded heaters, given in References 2-12 and 2-15.

More heat energy will be required if the windshield is defrosted indirectly by a moving air stream. Table 2-7 summarizes calculations of heat required for indirect heating of the windshield to meet FMVSS 103. This calculation is an approximation based on the windshield being uniformly heated by a constant temperature air stream. This approximation is justified, because only a small fraction of the energy in the air stream is transferred to the windshield. The moving air stream defroster system must supply about six times the heat required for the embedded defroster system.

It should be pointed out that typical defrosting systems have fully warmed up capacities many times this requirement. Typical defroster thermal capacity is 7.3 to 8.3 kW (25,000 to 30,000 Btu/hr), about 2 to 3 times the basic requirement. Part of this is conservative design practice. Examination of defroster performance data in actual FMVSS 103 tests reveals that typically the entire windshield is cleared in as little as 15 to 20 minutes, far in excess of the requirements. The large amount of excess capacity is partially to compensate for effects that are complex and difficult to model, such as entrainment of cold interior air in the

Table 2-6. Calculation of Energy Required to Meet FMVSS 103 Defrosting Requirements (Embedded Heat Source)

Initial Conditions

Window and Ice at -18°C (0°F)
Ice Coating = 0.44 kg/m2 (0.01 oz/in^2)

Physical Properties

Windshield (References 2-4 and 2-13 for laminated windshield)

- Thickness = 0.71 cm (0.28 in.)
- Conductivity = 6.34 watts/m-°C (0.315 Btu/ft-hr-°F)
- Specific Heat = 559 watts/m^3-°C (30 Btu/ft^3-°F)
- Area = 1.15 m^2 (12.35 ft^2)
- Emissivity = 0.94

Ice (Reference 2-3)

- Heat of Fusion = 334 kJ/kg (144 Btu/lb)
- Conductivity = 26.2 watts/m^2 (1.3 Btu/ft-hr-°F)
- Specific Heat = 8.46 kJ/kg-°C (0.487 Btu/lb-°F)

Free Convection Losses

h_f* = 0.19 $(\Delta T)^{1/3}$ on each side of windshield (Reference 2-11)

h_f = 3. watts/m^2-°C (0.6 Btu/hr-ft^2-°F) at 0°C (32°F)

Maximum convection losses = 139 watts (474 Btu/hr)

Radiation Losses

From both sides of windshield with T_a = -18°C (0°F) or 255°K (460°R) and T_w = 0°F (32°F) or 273°K (492°R)

Maximum radiation loss* = 2 x .171 x Emissivity x Area x $[(T_w/100)^4 - (T_a/100)^4]$ = 161 watts (548 Btu/hr)

Warm Up Energy Required

Energy to Warm Window with Ice and Melt Ice (-18°C to 0°C or 0°F to 32°F) = 133 watts (454 Btu)

Total Defrost Energy (30 minute test period) = 283 watt-hrs (965 Btu)

---

*Formulae are for English Units.

Table 2-7. Calculation of Energy Required to Meet FMVSS 103 Defrosting Requirements (Moving Air Stream)

Approach

Compare energy required to heat incoming air to energy transferred from air stream to windshield. Thus:

$$E_{AIR} = V_L (\Delta T)\ t\ C$$

where

E_{AIR} = total energy added to air stream by defroster

V_L = volume flow rate

ΔT = difference between air temperature and ambient

C = specific heat of air (volume basis)

t = operating time

And:

$$E_W = h_f (\Delta \bar{T})\ t\ A$$

where

E_W = total energy transferred to windshield by air stream

h_f = interior heat transfer coefficient

$\Delta \bar{T}$ = difference between air temperature and windshield

A = windshield area

Combining the two equations and cancelling common terms:

$$E_{AIR}/E_W = V_L\ C\ \Delta T/h_f\ A\ \Delta \bar{T}$$

However, based on data in Reference 2-11, it is found that for high defroster blower rates, h_f is a linear function of the blower air flow V_L. This neglects any free convection effects. Thus:

$$h_f = W\ V_L \text{ (where W is determined from data in Ref. 2-11)}$$

$$E_{AIR}/E_W = C\ \Delta T/WA\ \Delta \bar{T}$$

Table 2-7 (Continued)

Data

$C = 5.08\ kJ/m^3\text{-}°C$ (0.0183 $Btu/ft^3\text{-}°F$) at 15°C (59°F)

$A = 1.15\ m^2$ (12.35 ft^2)

$W = 6.66 \times 10^{-2}$ watt-hrs/m^5-°C (3.33×10^{-4} Btu/ft^5-°F) based on h_f = 23 watts/m^2-°C (4.0 Btu/hr-ft^2-°F) for V_L = 340 m^3/hr (200 cfm)

$\Delta T/\Delta\bar{T} = 1.31$ (for 57°C (135°F) defroster outlet temperature)

Results

$E_{AIR}/E_W = 5.82$

If E_W = 283 watt-hrs

E_{AIR} = 1.65 kWh

defroster jet, and lateral spreading of the defroster jet. There is also considerable variation in temperature over the windshield. Defroster overdesign tends to compensate for these limitations on real designs.

With an embedded heat source, it is easier to ensure an even heat supply to the windshield, with much less total energy. Electric and hybrid vehicles are compatible with the use of electrically conducting films, which can provide uniform windshield heating. This is because the propulsion battery can provide adequate voltage and power levels (References 2-12 and 2-15) to operate these systems.

2.3.2 Dynamic Deicing and Defogging Requirements

Two additional conditions which are potentially hazardous for vehicle operation are windshield icing and fogging during vehicle operation. These conditions are not directly measured by FMVSS 103. Part of the difficulty in establishing standards for these conditions is the difficulty in easily simulating them in a laboratory test.

References 2-11 and 2-16 have investigated the conditions to be used as criteria to prevent icing and fogging. These conditions are as follows:

> Icing Prevention: Maintain the outside windshield surface temperature above 0°C (32°F), in a -4°C (25°F) ambient temperature with the vehicle speed of 48 kph (30 mph).
>
> Defogging Prevention: Maintain the interior surface of the windshield above the vehicle's interior dew point in a 0°C (32°F) freezing rain.

The energy requirements to satisfy these conditions were calculated in Reference 1-1. The icing prevention condition requires less energy than is required to meet FMVSS 103. Defogging requires a very high energy level to directly heat the windshield. However, with a moving air stream defroster, approximately the same energy level is required as for FMVSS 103. Hence, FMVSS 103 essentially governed the defroster functional requirements.

2.3.3 Discussion of Functional Requirements

The functional requirements for the vehicle defog and defrost systems are summarized in Table 2-8. Where different requirements were needed to satisfy different operating conditions, only the more stringent requirements were listed. The basic assumptions behind the requirements

Table 2-8. Functional Requirements for Defroster and Defogger

1. Air stream heater for defogging of 3.3 kW (11,500 Btu/hr) with air flow of 340 m^3/hr (200 cfm). Heat requirement reduced about one third by recirculating air from vehicle's interior.

2. Time to reach full capacity of less than 10 minutes.

3. Optional: embedded heater for defrosting and FMVSS 103 test of 0.6 kW (based on power level obtained in Table 2-6).

4. Meets general requirements of Table 2-5.

are also summarized. A blower capacity of 340 m^3/hr (200 cfm) was included to ensure good heat transfer to the windshield. The total capacity requirement can be reduced by recirculating warm air from the passenger compartment through the defroster, in lieu of using cold outside air. However, the analysis of requirements is based on simplified physical assumptions. Real systems generally have considerable excess capacity. Hence, the use of design safety factors is advisable if higher capacities do not imply excessive cost or weight penalties.

The use of a two mode system, with an embedded windshield heater as well as a moving air stream defroster, can also be considered if the cost penalty is not excessive.

2.4 BATTERY TEMPERATURE CONTROLLER

2.4.1 Desired Battery Temperature Range

In order to maintain the electric vehicles modest performance capability in acceleration, hill climbing, and top speed, it is desirable to maintain the battery performance at close to maximum remaining capacity. The JPL Guidelines (Reference 2-9) suggested that the battery controller try to maintain the battery at the controller set point of 49°C (120°F), with a temperature range of 43°C to 54°C (110°F to 130°F).

There are varying opinions in the literature (References 2-17 and 2-18) suggesting temperature ranges of 35°C (95°F) to 49°C (120°F) as "best" for lead acid storage battery operation. In general, there is very little data supporting these claims, specifically for vehicle traction batteries. In the final analysis, this is not a problem, since the ECS design can be easily modified to maintain the battery at other temperatures.

Battery Freezing

A second concern on battery performance is potential damage from freezing of the electrolyte during a "cold soak" period. The freezing point of the electrolyte is a function of electrolyte specific gravity. For a fully charged battery with a high specific gravity the freezing point is well below the vehicle design temperature range. However, when the battery is completely discharged, a potential freezing danger does exist unless the battery is maintained above -4°C (25°F).

Thus, long term storage of the electric vehicle at low temperatures presents a unique problem. If the battery is charged before the storage begins, the battery controller can allow the battery to "soak" at the ambient temperature, with no danger of freezing. This approach requires no energy for the duration of the storage period. To reactivate the vehicle, the battery would have to be rewarmed to the operating temperature range.

If the vehicle is stored with the battery discharged, then freezing of the electrolyte is a potential problem. Sufficient heat would need to be supplied to maintain the battery at about -4°C (25°F) or higher to ensure against electrolyte freezing.

Operating Scenarios

The functional requirement for the battery temperature controller is the capability to maintain the battery temperature level in the operating range under a variety of conditions. The conditions used in determining this functional requirement are as follows:

1. Trip Conditions
   a. Work Trip (10 'D' cycles)
   b. Family Business Trip (6 'D' cycles)
   c. Maximum Range Trip (66 'D' cycles)
2. Charging - 8 hour recharge
3. Maximum Power (i.e., hill climbs) - 3 to 5 times average power output over 'D' cycle.

2.4.2 Battery and Container Thermal Model

Battery characteristics are taken as those provided in Reference 2-9 (dated 4/24/80). These specify the heat generated by the battery during the charging and discharging cycles and are taken to represent the heat sources within the battery. The battery pack is assumed to be at almost uniform temperature throughout by virtue of convective circulation of the electrolyte and the high thermal conductivity of the internal parts. Thus, the battery is considered as a homogeneous mass with a specific heat as given in Attachment D. If the battery is in a perfect insulated box, then it will undergo the temperature rises calculated in Table 2-9 for the different operating modes.

Table 2-9. Summary of Battery Heat Generated and Temperature Change for Different Operating Modes

Trip Conditions

1. Heat released per battery per "D" cycle = 0.22 watt-hr (0.78 Btu)

2. Temperature change in battery per "D" cycle = 0.028°C (0.05°F)

3. Temperature change in battery for maximum range trip = 1.8°C (3.3°F)

Charging (Daily Charge+)

1. Temperature change in battery during recharge++ = 12°C (22°F)

2. Heat release by battery pack during recharge = 1799 watt-hr (6138 Btu)

3. Heat release rate for 8 hour recharge period = 225 watts (767 Btu/hr)

Maximum Load

Temperature rise during maximum load should not exceed total temperature rise during driving. Temperature rise for a "D" cycle at 10 times normal losses would only be 0.28°C (0.5°F).

+Weekly equilization charge is 20% higher.

++Assuming no heat loss.

Table 2-9 summarizes the heat releases for a 'D' cycle and during charging. Heat releases for the trip scenarios are taken as the product of the heat release per cycle and the number of cycles in the trip. It is seen that charging is a critical mode.

Container Effects

The battery pack is assumed to be in a container which provides structural support and thermal insulation from ambient conditions. Modeling of the battery container is a more complex problem because the thermal properties of the container affect the functional requirements of the battery controller. However, since cooling can be provided by forced ventilation with ambient air, a low thermal conductance container appears desirable.

This report adopted the approach that the thermal conductance of the battery container should be an aid in maintaining the battery in its operating temperature range during normal operation and charging. This is similar to the approach recently reported for battery insulation in Reference 2-17. As shown in Table 2-10, this level of thermal conductance can be easily obtained by insulating the battery case with 2.54 cm (1 inch) of mineral fiber insulating material.

2.4.3 Heating and Cooling Loads

Battery cooling is assumed to be accomplished by moving ambient air through the battery compartment. This also satisfies the ventilation requirement. The fan required to cool the batteries during driving and (8 hour) recharging is calculated in Table 2-10. The fan would be activated by a thermal switch whenever the batteries exceeded the preset temperature. Under most conditions, the fan would cycle on and off as needed to limit battery maximum temperatures.

If the vehicle was left idle at low ambient temperatures for short periods, then a small heater could be used to maintain the operating temperature. Table 2-11 gives the energy required for such a maintenance heater, based on the assumed battery container.

On the other hand, if the battery has been allowed to cold soak, considerable amounts of energy are required to bring it to operating conditions again (Table 2-11) This energy most likely would have to be

Table 2-10. Summary of Calculations for Battery Container Characteristics

1. Normal Driving Heat Release Rate ("D" Cycle) = 121 watts (412 Btu/hr)

2. Normal Charging Heat Release Rate (8 hour basis) = 225 watts (767 Btu/hr)

3. Surface Area of Battery Container = 3.4 m^2 (37 ft^2)
   (Based on 18 cells stacked width-wise in a battery tunnel.)

4. Required battery temperature to be maintained = 49°C (120°F) with ambient at -29°C (-20°F)

5. Required thermal conductance of container to maintain battery at 49°C (120°F) with normal driving heat release rate, at -29°C (-20°F) ambient = 0.45 watts/m^2-°C (0.08 Btu/hr-ft^2-°F)

6. Insulation Properties -

Mineral Fiber	3.6 W-cm/m^2-°C (0.25 Btu-in/hr-ft^2-°F)
Cellular Glass	5.8 W-cm/m^2-°C (0.40 Btu-in/hr-ft^2-°F)
Fibrous Glass	4.3 W-cm/m^2-°C (0.30 Btu-in/hr-ft^2-°F)

7. Supplemental energy required to maintain battery at 49°C (120°F) with one inch of mineral fiber insulation at normal driving heat release rate at -29°C (-20°F) ambient = 260 watts (888 Btu/hr)

8. Cooling fan required to dissipate battery heat released during 8 hour charge with a 5.5°C (10°F) rise in cooling air = 120 m^3/hr (70 cfm)

Table 2-11. Summary of Energy Required to Recover Battery Pack from "Cold Soak"

1. Energy to raise battery pack from cold soak at -29°C (-20°F) to minimimum operating temperature of 18°C (65°F) = 7.0 kWh (23868 Btu)

2. Energy required to maintain battery pack temperature at 49°C (120°F) with one inch (2.54 cm) of mineral fiber insulation = 380 watts (1295 Btu/hr)

supplied by a source other than the vehicle battery, since it represents a significant fraction of the rated battery capacity. More heat must be delivered if the warmup time is long, because of losses through the battery container.

2.4.4 Discussion of Functional Requirements

The key functional requirements for the battery temperature controller are summarized in Table 2-12. The requirements are based on the batteries being insulated with 2.54 cm (1 inch) of mineral fiber insulation, to reduce the heating load needed to maintain the battery at the desired temperature. This seems to be the most effective configuration, though other variations on this design are possible.

The controller requirements are based on the fact that the battery has a fairly broad operating temperature range. Under a broad variety of operating conditions in milder climates, no battery temperature control is required. When the temperature limits are exceeded, the controller would activate the heating or cooling system as required. The system could be easily redesigned for lower battery temperatures.

The key problems in meeting the functional requirements are recovering from "cold soak" and faster charging. Cold soak recovery energy would most likely come from either a fossil fuel heater, or the charging station. Faster charge rates may require more heat removal capacity than can be provided by forced ventilation of the battery compartment. Improved means of cooling the batteries could also include:

- Use of extended surfaces on the battery cases and containers
- Use of liquid cooling loops in the battery cases

However, these were not found to be necessary in typical automotive service, especially if charging is done overnight.

2.5 SUMMARY OF FUNCTIONAL REQUIREMENTS

2.5.1 Integration of Requirements

The individual requirements for the key ECS elements have been discussed in Sections 2.2 through 2.4 and summarized in Tables 2-5, 2-8, and 2-12. These requirements were developed on the basis of the systems being completely independent and not interconnected.

Table 2-12. Battery Temperature Controller Functional Requirements

Assumptions

1. Batteries as specified in Reference 2-15.
2. Battery packaged widthwise in vehicle. Thermal conductance of container to ambient 4.9 watts/°C (9.3 Btu/hr°F).

Controller Requirements

1.	Minimum Battery Temperature (Operating mode - no heat supplied in cold soak mode)	= 18°C (65°F)
2.	Maximum Battery Temperature (Maximum cooling demanded at this temperature - Separate requirements will be developed in Section 7.1)	= 49°C (120°F)

Heating and Cooling Requirements

1.	Maximum Heat Required to Maintain Operating Temperature at 49°C (120°F).	= 380 watts (1295 Btu/hr)
2.	Minimum Heat Energy Required to Recover from Cold Soak Conditions	= 7.0 kWh (24,000 Btu)
3.	Maximum Heat Removal Rate (Based on 8 hour charging cycle)	= 225 watts (767 Btu/hr)
4.	Cooling Fan Flow Required to Remove Charging Heat Release (Based on 6°C (10°F) air temperature rise and 8 hour charge period)	= 120 m^3/hr (70 cfm)

However, there is a strong case for integrating the systems. The goal of such integration is to reduce the number of redundant systems contributing to vehicle weight, volume, complexity and cost. The key area for system integration appears to be the use of a common heat source for passenger compartment heating, windshield defrosting and defogging, and battery recovery from "cold soak". This approach is an extension of the common heating, defrosting and defogging systems already found on current heat engine vehicles.

Integration of the battery cooling requirement and passenger compartment cooling requirement is also possible. It should be noted that the passenger compartment cooling requirement exceeds the battery cooling requirement by a large factor, unless very short charging times are considered. However, (as noted in Section 7.1), battery cooling can be accomplished with ambient air.

Preliminary Integrated Design

Figure 2-7 shows a schematic of an integrated ECS design with recirculation and limited ventilation flow. Integration of the passenger compartment heating and cooling system with the defroster and defogger air flow would follow current practice. When defrosting and defogging is required, the heater output is diverted to the defroster jets. The air conditioner uses the same blower and duct work as the heating system. Additional ducting to handle the return flow could be integrated into the vehicle body structure between the inner and outer body panels. Choice of the inlet and exhaust points on the vehicle envelope would ensure satisfactory performance of this system at different vehicle speeds. The blower speed would be varied by the vehicle operator, as in current design practice.

The battery compartment temperature is integrated with the passenger compartment ECS in order to reduce the number of heating and cooling units. The heating unit would be used at full capacity to supply the heat required to recover from the "cold soak" condition. It could also be used to maintain the battery temperature in cold weather operation. Potentially, the passenger compartment cooling unit could provide most battery cooling requirements, though this is normally supplied by outside air. A separate

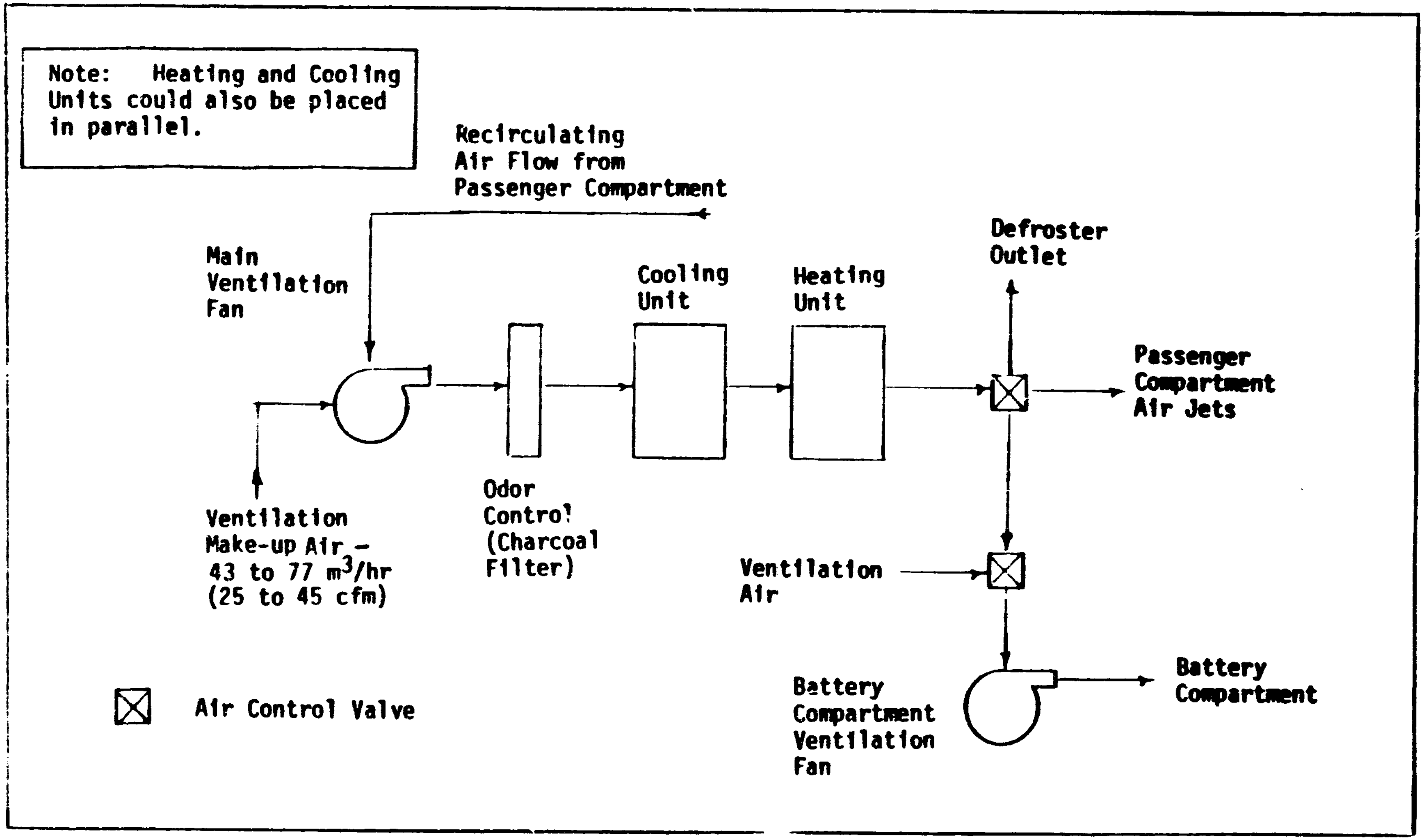


Figure 2-7. Schematic of Integrated ECS Design

blower is used to provide positive ventilation of the battery compartment and to ensure that battery fumes are not returned to the passenger compartment.

The potential embedded heaters in the windshield and battery compartment are not shown in Figure 2-7.

2.5.2 Summary

Table 2-13 summarizes the functional requirements of the integrated system. The summary indicates which elements determine the requirements.

Table 2-13. Summary of Functional Requirements for Integrated Environmental Control System

Heating Requirements

1. Capable of maintaining a temperature of at least 18°C (65°F) in passenger compartment at -29°C (-20°F) ambient.

2. Heating capacity 5.7 kW (19,000 Btu/hr) with full ventilation load. Design range is 2.2 to 2.8 kW (7,500 to 9,500 Btu/hr) with controlled ventilation.

3. Time to reach full capacity is less than 10 minutes.

4. Maximum air flow capacity of 1100 m^3/hr (200 cfm) for defroster.

5. Heat can be directed to passenger compartment, defroster jets, or battery compartment.

6. Optional: embedded electrical heat source of 0.6 kW in windshield.

7. Heater can recover battery from "cold soak" in less than 4 hours.

Cooling Requirements

1. Capable of maintaining a temperature of 25°C (77°F-RH 40%) in passenger compartment at 49°C (120°F) (29°C (85°F) wet bulb) ambient.

2. Cooling capacity 7.5 kW (25,500 Btu/hr) with full ventilation load. Design range is 3.2 to 4.1 kW (11,000 to 14,000 Btu/hr) with controlled ventilation.

3. Time to reach capacity less than 3 minutes.

4. Time to produce comfort for front seat passengers less than 10 minutes.

5. Optional: cooling air stream can be directed to battery compartment.

General Requirements

1. Capable of withstanding mechanical, thermal, vibrational, and acceleration environment of electric or hybrid vehicles.

2. System completely sealed and designed so combustion air and exhaust products do not enter passenger compartment.

3. Minimizes use of hazardous materials which could be released in normal operation or accidents.

4. Capable of being packaged and integrated into the vehicle system.

3.0 DEVELOPMENT OF THE RATING SCHEME

3.1 METHODOGY AND SELECTION OF FACTORS

3.1.1 Overview and Guidelines

A suitable rating or evaluation scheme is essential for selecting the best ECS elements and the best integrated ECS. A good rating scheme should include consideration of the key parameters of cost and performance. It should also account for the ECS's impacts on the vehicle's propulsion system and on potential users. The rating scheme formulation must take into account the uncertainties in the ECS parameters. This includes characteristics of emerging ECS technologies which have yet to reach the commercial market. Because of uncertainties in the data, increasing the number of parameters in the rating scheme does not necessarily increase accuracy.

The rating scheme is developed as a two step process. The first is a broad screening process using many criteria but requiring lower quality information. This step eliminates most of the unsuitable candidates. The second is a more detailed evaluation to select the "best" among suitable candidates. This step is quantitative and requires higher quality input data.

Guidelines

Several guidelines for developing this rating scheme are borrowed from Reference 3-1. The key guidelines emphasized in developing the rating scheme are:

- o Good analysis is the servant of judgment, not a substitute for it.
- o It's better to be roughly right than exactly wrong. (Make sure you evaluate all the alternatives, even if you cannot provide a sophisticated analysis of each.)
- o Keep it simple.

The rating scheme development is in accordance with the guidelines suggested by JPL in Reference 1-5. Separate evaluations are performed on the heating and cooling system elements. The highest ranking candidates are then combined to produce integrated ECS's. A second evaluation step selects the "best" ECS alternative. This scheme is summarized in Figure 3-1.

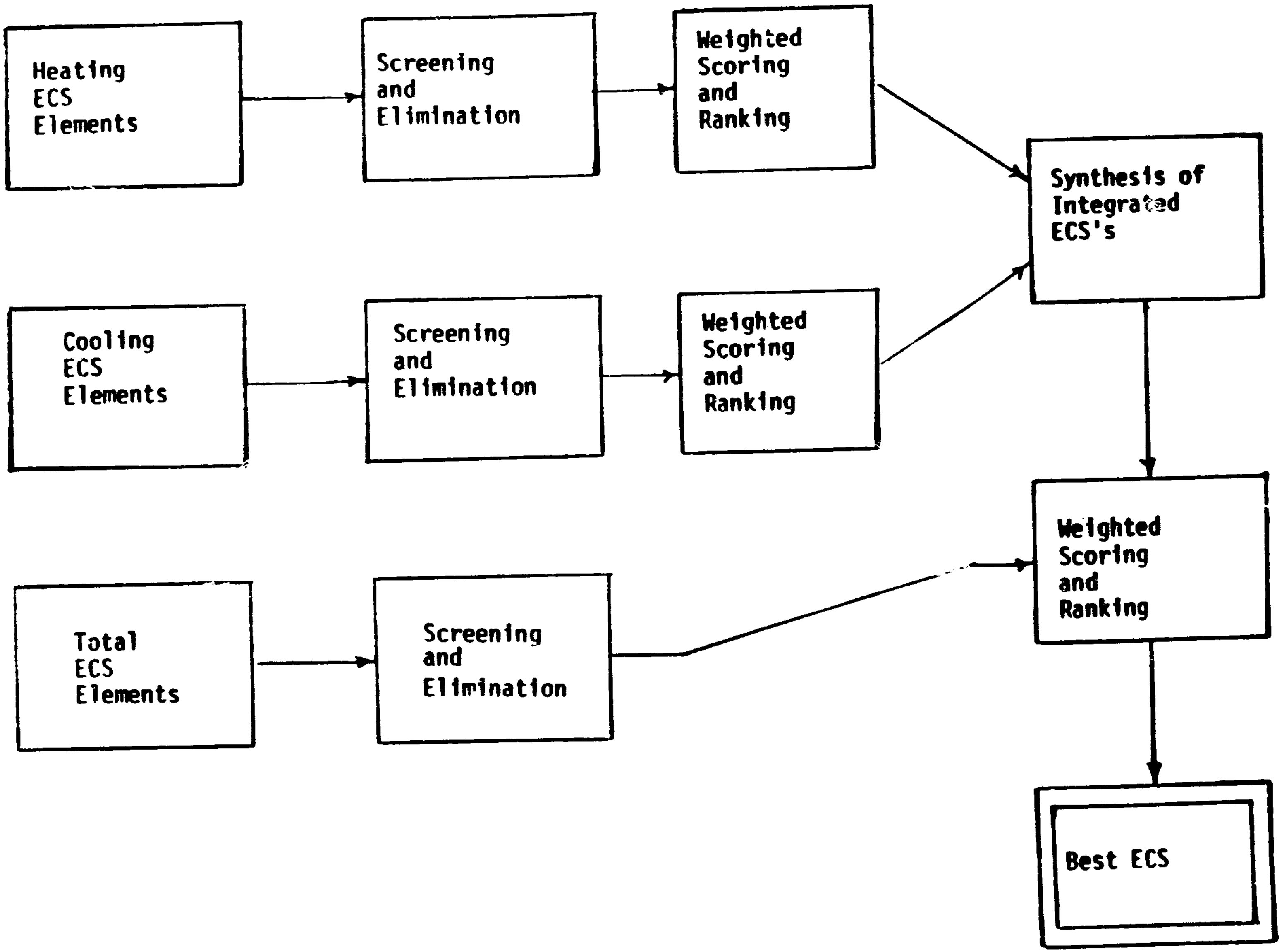


Figure 3-1. Overview of Rating Scheme for Environmental Control Subsystems

The evaluation of the candidates is a two step process. First, broad screening criteria are constructed to eliminate alternatives which clearly cannot meet minimum requirements or are clearly not competitive. These ECS's would be eliminated as inappropriate. This allows the evaluation to focus on the stronger alternatives.

3.1.2 Scoring Models

The remaining ECS elements would be evaluated in more detail with a "scoring model". In the "scoring model", each alternative ECS element is described by a series of parameters called rating factor scores. A rating factor score measures how well a particular ECS alternative meets a particular functional requirement or JPL guideline compared to the other alternatives. It can also establish how well a new technology compares with current (or baseline) technology.

The rating factor score for each parameter compares the value of that parameter for a particular technology to a baseline value. The baseline values are derived from the characteristics of current ECS technology, the ECS functional requirements, or the JPL guidelines. The rating factor score can be represented in functional form as follows:

$$\text{Rating Score} = f\ (\text{Actual value/Baseline value})$$

The overall merit of a particular ECS alternative is measured by its total score. The total score for each alternative is the sum of the rating factor scores for each parameter times the appropriate weights. The weights are normalized so their sum is unity. The total score for an ECS element is given by:

$$\text{Total Score} = \sum (\text{Rating factor score})\ (\text{Weight})$$

The ratings for the integrated ECS will be based on the same rating scheme used to evaluate the individual ECS elements.

Experience with "scoring models" used to evaluate energy technologies in Reference 3-2 has shown that "good" technologies will score well in this type of rating system. This is regardless of specific differences in the actual scoring and weighting procedures. Thus, scores and rankings of ECS elements and integrated ECS's should be fairly insensitive to slight shifts in the weights themselves. During the evaluation procedure, the sensitivity of the results to the weights are tested. This ensures that the rankings represent significant differences between the ECS elements.

3.1.3 Factors in the Rating Scheme

Factors considered in the rating scheme are drawn from two sources; the JPL guidelines (Reference 1-5), and the Functional Requirements report (Reference 1-1).

JPL Guidelines

JPL guidelines which directly establish factors for the rating scheme are listed in Table 3-1. In cases where the guidelines have been interpreted, the interpretation is given in parentheses. The guidelines set norms or bounds for certain rating factors. These are explicitly stated where applicable.

Functional Requirements

The functional requirements also directly establish factors for the rating scheme. The principal requirements are listed in Table 3-2. The functional requirements are broken down separately for the heating and cooling ECS elements. An ECS would be required to have at least one heating and one cooling element, except where a heat pump can perform both functions.

System Sizing

An important variable in evaluating various ECS's is system capacity. The evaluation procedure requires the ECS element to have the required design range capacity levels given in Table 2-5. The characteristics of the technology at those capacity levels will then be used in the evaluation.

3.1.4 Quality of Information Available

It is important to match the data requirements of the rating scheme to the input data available. Adequate data quality is important, especially for numerical calculation of rating score in the second and third steps of the evaluation process. Lower quality data and qualitative (non-numerical) data is adequate for the initial screening process.

Table 3-1. Rating Scheme Factors from JPL Guidelines

Cost

"The production line version of those ECS's selected for prototype development should be available to the consumer at reasonable cost." (ECS cost to consumer should not exceed 2 to 3 times conventional ECS costs.*)

Impact on Vehicle Characteristics

"As a goal, the combined volume of the ECS elements excluding ducting shall be less than 0.17 m^3 (6 ft^3)." (Upper bound for ECS impact on vehicle characteristics.)

"As a goal, the ECS shall not decrease Electric Vehicle range by more than 20% as estimated by the equation defined in Task (7) (A) (ii)." (Upper bound for ECS impact on the vehicle characteristics.)

Source: Attachment A, Reference 1-5.

*For high cost optional ECS elements, such as the air conditioner, this cost ratio should be even lower. Consumers are more conscious of these costs because they are made explicit when the vehicle is purchased, and not included in the vehicle's "base" cost. Hence, the cost of the cooling ECS is limited to 2 times current ECS costs. However, the heating ECS could be 3 times the current ECS costs.

Table 3-2. Example of Rating Scheme Factors from the Functional Requirements

Performance Factors

(Heating System)

- Design range in 2.2 to 2.8 kW (7,500 to 9,500 Btu/hr) with controlled ventilation (Recirculating system).
- Time to reach capacity is less than 10 minutes (from cold soak start).
- Heater can raise battery temperature to operating range from "cold soak" in less than 4 hours.

(Cooling System)

- Design range is 3.2 to 4.1 kW (11,000 to 14,000 Btu/hr) with controlled ventilation (Recirculating system).
- Time to reach capacity is less than 3 minutes (from hot soak start).
- Time to produce comfort for front seat passengers 10 minutes.

Other Factors (All Systems)

- Capable of withstanding mechanical, thermal, vibrational and acceleration environment of electric or hybrid vehicles.
- System completely sealed and designed so combustion air and exhaust products do not enter passenger compartment.
- Minimizes use of hazardous materials which could be released in normal operation or accidents.
- Capable of being packaged and integrated into the vehicle system.

NOTE: Actual evaluations will be done for a specific system size, once the parameters affecting system size are evaluated or selected.

Source: Reference 1-1

An investigation of information available showed that fairly high quality data was available for the following:

- Cost
- Impacts on Vehicle Characteristics (Weight, Volume, and Energy Use)

For most technical options, this data was adequate to support the detailed numerical evaluation required in the rating scheme.

By contrast, the data quality for evaluating other factors was generally poor. Thus, these other factors were used for eliminating "inappropriate" ECS elements (in Task 5), but not for detailed numerical evaluations.

3.2 FORMAT FOR RATING SCHEME FACTORS

3.2.1 Overview

This section develops the functional forms used to calculate the rating scores of the major factors in the quantitative rating scheme. For ease of calculation, the numerical score has been selected to have a range of 0 to 100. A score of 100 indicates the parameter is equivalent to the baseline value (see Section 3.1.2). If the parameter varies from the baseline value in a favorable manner, the score will initially be taken to be 100.

The rating goes down if the parameter varies from the baseline value in an unfavorable manner. In general, the factor will be assigned a low score if the parameter is at it's acceptable limits. Also, the evaluation parameters discussed are only unacceptable if they exceed a given upper limit. For simplicity in calculating the actual scores, a linear relationship is established between the rating score and the actual value of the parameter. The baseline value of the parameter enters the calculation of the rating score as shown:

$$\text{Rating Score} = f\ (\text{Actual Value}/\text{Baseline Value})$$

As an example, the functional form of f could be chosen so that: $f(1.0) = 100$ and $f(\text{Actual value} \rightarrow \text{Acceptable Limit}) \rightarrow 25$. The value of 25 would be selected to provide a suitably low score. This approach avoids having negative rating scores if the acceptable limit for a parameter is slightly exceeded.

For any given parameter, the baseline value and acceptable limit will vary, depending on whether the evaluation is for an ECS element or an integrated ECS. The baseline value and acceptable limit for a parameter may also vary if the evaluation is for a hybrid versus an electric vehicle. Choosing different baseline values and acceptable limits essentially varies the functional form to that required for each evaluation step. The functional form can also be varied by chosing another value for f(1), i.e., f(1) = 25.

The technologies being evaluated in this process differ widely in their degree of development. To ensure that the comparisons are fair, the rating process is subdivided so only technologies at the same level of development are compared. See Section 3.2.4.

3.2.2 Cost Factors

A key rating parameter of the integrated ECS is first cost to the vehicle owner. Baseline costs can be established on the basis of current heating and cooling systems. Table 3-3 gives the current heater-defroster cost. Because the defroster is required on every vehicle, there is a strong incentive to keep its cost low. Air conditioning, by contrast, is still a buyer option. Air conditioning costs are generally higher, as shown in Table 3-3.

Any ECS with first costs equal to or lower than these baseline values would receive a cost score of 100. For the air conditioner, if the cost exceeded the baseline value by a factor of 2 or more, the market ity of that air conditioner would be very low. Thus it would be assigned a low rating score (zero). The Type A functional form shown in Figure 3-2 satisfies these conditions, and therefore would be used to calculate the cost score for the air conditioner. The cost for the heater-defroster could have a higher acceptable limit, perhaps three times the baseline value. Hence, the rating functional form for the cost of the heater would be the adjacent curve shown in Figure 3-2. An average of these two curves is used for the total ECS.

Table 3-3. Estimated Cost for Vehicle Heater-Defroster and Air Conditioners (Current Heat Engine Vehicles)

Item	Current Cost ($)
Heater Core	18 - 30
Blower	25
Water Hose	5
Total Heater	48 - 60
Complete 5.86 kW (20,000 Btu/hr) Heater with Fan and Hose	85
Small Vehicle A/C	412 - 421*
Large Vehicle A/C Without Temperature Control	438 - 471*
Large Vehicle A/C With Temperature Control	473 - 530*

*Dealer's base cost (not manufacturer's suggested list price).

Source: References 3-3 and 3-4.

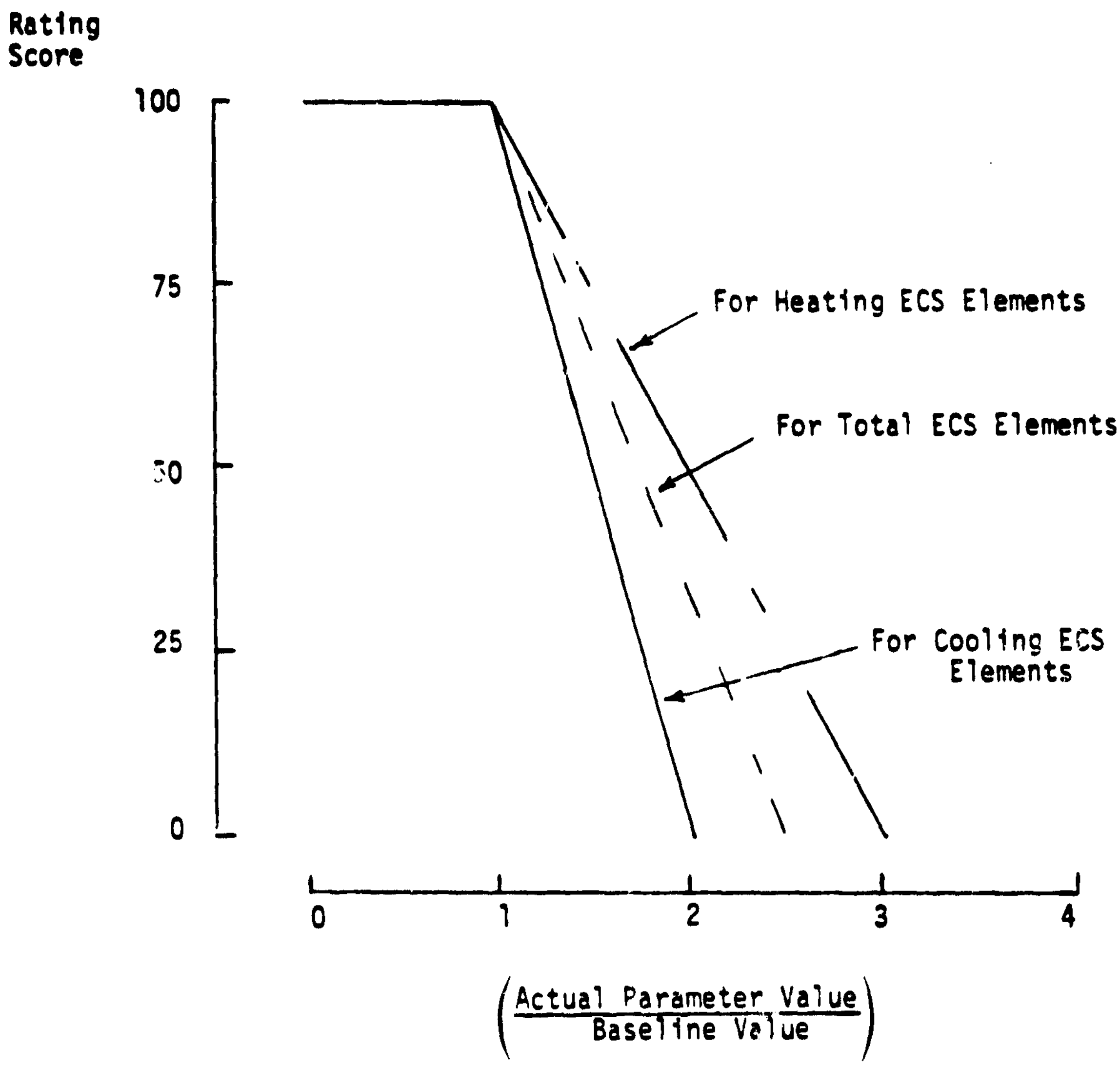


Figure 3-2. Type A Functional Form for Cost Parameters

3.2.3 Impacts on Vehicle Characteristics

The three major impacts of the ECS on the vehicle are additional weight, volume, and energy use. All three factors can be evaluated individually. However, they also have a collective impact on vehicle range. The impact of these factors on vehicle range will be evaluated separately in Section 5.0.

Weight

Weight of alternative systems could easily exceed baseline values for current systems. System weight will include the weight of the associated energy storage. Systems weighing more than three times current systems would tend to have a significant impact on the vehicle's acceleration. These systems are clearly inappropriate. However, any additional weight in the electric vehicle is undesirable. It is desireable to reduce the ECS weight to as low a level as possible. Hence, use of the Type B functional form, shown in Figure 3-3 seems appropriate.

The Type B functional form is not significantly different from the Type A functional form. In general, the lower a parameter's value, the higher the rating score. The key difference is that the Type B functional form emphasizes reduction of the parameter's value to as low a level as possible. For weight, this appears to be a desirable goal. Hence, the Type B functional form is used.

Volume

The upper limit for the volume of alternative systems has been set by the JPL guidelines (Reference 1-5, Attachment A). Ideally, this ECS parameter should be as small as possible. Hence, the format of the rating function will also be functional form Type B.

Energy Use

Energy use by the ECS in general should be minimized. Although upper limits for energy use were set by the JPL guidelines, typical ECS energy use was significantly lower than these levels. However, since a minimum level of energy use is sought, use of the Type B functional form is appropriate.

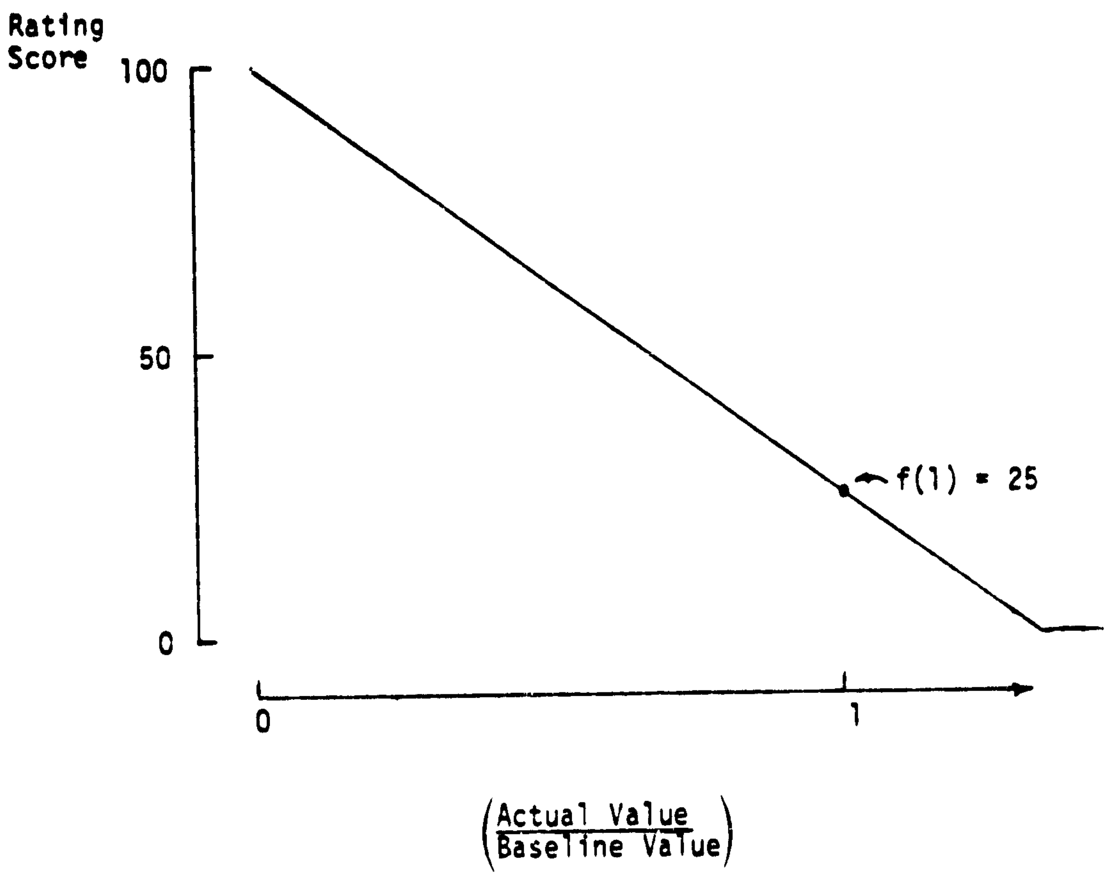


Figure 3-3. Type B Functional Form for Weight, Volume, and Energy Use Parameters

3.2.4 Status of Technical Development

The ECS elements being examined in this study utilize technologies in varying states of development. Some ECS elements are commercially available today, although perhaps not in a form suitable for automotive use. Other ECS elements utilize technology in hardware development and evaluation for eventual large-scale production. Many ECS elements are based on concepts which have yet to be reduced to practice. Comparing ECS's whose technical development is in such diverse states is logically incorrect. This is because the technologies will not be ready in the same time frame.

Also, the Statement of Work (Task 7, Reference 1-5) requires a separate evaluation of the "best" ECS for:

- Immediate prototype development
- More extensive prototype development

Hence, the evaluation of development status is a required part of the rating scheme.

Table 3-4 establishes the definitions for the state of development that this study will utilize based on the suggestions in the Reference 1-5. The evaluation will treat the first two cases separately. Only a near-term ECS will be recommended for immediate development. A mid-term ECS would be recommended for more extensive development only if it appeared to be very attractive compared to the near-term system. Long-term systems are considered "out of scope" in this study.

3.3 SELECTION OF WEIGHTS

3.3.1 Basis for Weights

Selection of weights for the various rating factors is a subjective process. A limited survey of values was made to aid in the selection of weights. The survey included six study participants and members of the TRW staff associated with the project. The key point in this survey was the requirement that the team summarize both its own values, and its perception of public values. Public values are the individual's perception of how the general population would respond to this survey.

Table 3-4. Definitions of Development Status

Near-Term - Prototype development mainly requires integration and adoption of existing proven system elements. (Includes systems commercially available)

Development effort of 1-2 years. Production potential by 3-5 years.

Mid-Term - Prototype development requires further experiments on systems currently at laboratory stage. System integration cannot begin for some time.

Development effort of 2 to 5 years needed. Production potential by 6-10 years.

Long-Term - Development from new concepts. Complete hardware test and development cycle required. (Out of study scope).

It is difficult to draw any definite conclusions from such a limited survey. Two observations, however, may be relevant. First, it was noted that the perceptions of the public values are diffuse; that is, they tend to have a wide distribution. This implies that the factors tend to be perceived as almost equal in relative importance, at least as far as this limited survey shows. Second, the diffuse results imply that small changes in the weights should not produce significant changes in the overall scores for different ECS alternatives. This conclusion is also supported by work with "scoring models" reported in Reference 3-2. Which technologies score well in an evaluation procedure should be relatively insensitive to the choice of weights. Relative scores which are overly sensitive to the choice of weights do not clearly discriminate between the technical alternatives.

3.3.2 Weights Selected

Weights were selected as indicated in Table 3-5. The weights reflect a "best" engineering judgment. Cost was given the heaviest emphasis because it was directly perceived by the customer and the manufacturer alike. The factors causing impact on vehicle range are collectively nearly as important. That is, the customer will not be favorable to an ECS with a large range impact. However, it was not clear in advance that weight, volume, or energy use should be emphasized in this regard. Hence, the subfactors for weight, volume and energy use are essentially equal.

More Complex Weights

It should be noted that other factors requiring a more complex set of weights could be considered in the rating scheme. This could include factors such as the ECS impact on vehicle shape, or the consideration of different weights for energy drawn from the propulsion battery versus energy from an auxiliary liquid fuel supply. However, these factors were not considered because they appeared to add unnecessary complication to the rating scheme, with no advantage to the evaluation process.

3.4 APPROPRIATENESS FOR MARKET SIZE

In the automotive industry, the decision to produce and commercially market a new technology requires two conditions. The first is technical superiority of the new technology, i.e., better performance, lower weight,

Table 3-5. Weights Selected for Rating Scheme

Rating Factor	Weight (Normalized)	
Cost (Initial)	0.60	
Impact on Vehicle Range		
- Weight Factor	0.13	0.40
- Volume Factor	0.13	
- Energy Use Factor	0.14	
Total	1.00	

longer life, etc. The second factor is manufacturing superiority, i.e., the capability of being produced at lower cost, through savings in labor, materials, or requirements for production capital. The key to manufacturing superiority is mass production (Reference 3-5).

However, mass production requires a high level of consumption. The market for the product must be large enough to warrant the investment in production tooling needed for efficient mass production.

If consumption is not at a sufficiently high level, then the manufacturer has two choices. One, he can produce in limited quantities and much higher unit costs. As shown in Figure 3-4, the cost of limited production, i.e., a few thousand units per year, might be 50% higher than mass production (millions) costs. Where no technical alternatives exist, this is often the only choice. If the product markets well, even at the high price, the manufacturer can generate enough capital from early sales to finance expanded and more efficient production facilities.

However, if his product line is in a competitive market where cost is an important factor for market growth, other strategies may be more favorable. One alternate approach is to maximize use of component technologies already in mass production for other mass markets. Assemblies of those components which can meet his product requirements can be manufactured with limited investment on his part. Often he can obtain favorable prices from the component suppliers because he buys reasonably large quantities. His costs are mainly for assembly, which is only a fraction of the total production costs. While his system may not be technically optimal, its costs are competitive. As the market grows, he can eventually make the capital investment needed to produce the entire system, including all of the components, in his own plants.

Thus, if the ECS market for electric and hybrid vehicles remains fairly small, the appropriate choice for ECS technologies is from technologies (components) already commercially available. In the near-term, this is the most likely situation. Technologies which would require new investments in production facilities and would carry high unit prices in limited production are not desirable choices for a small market.

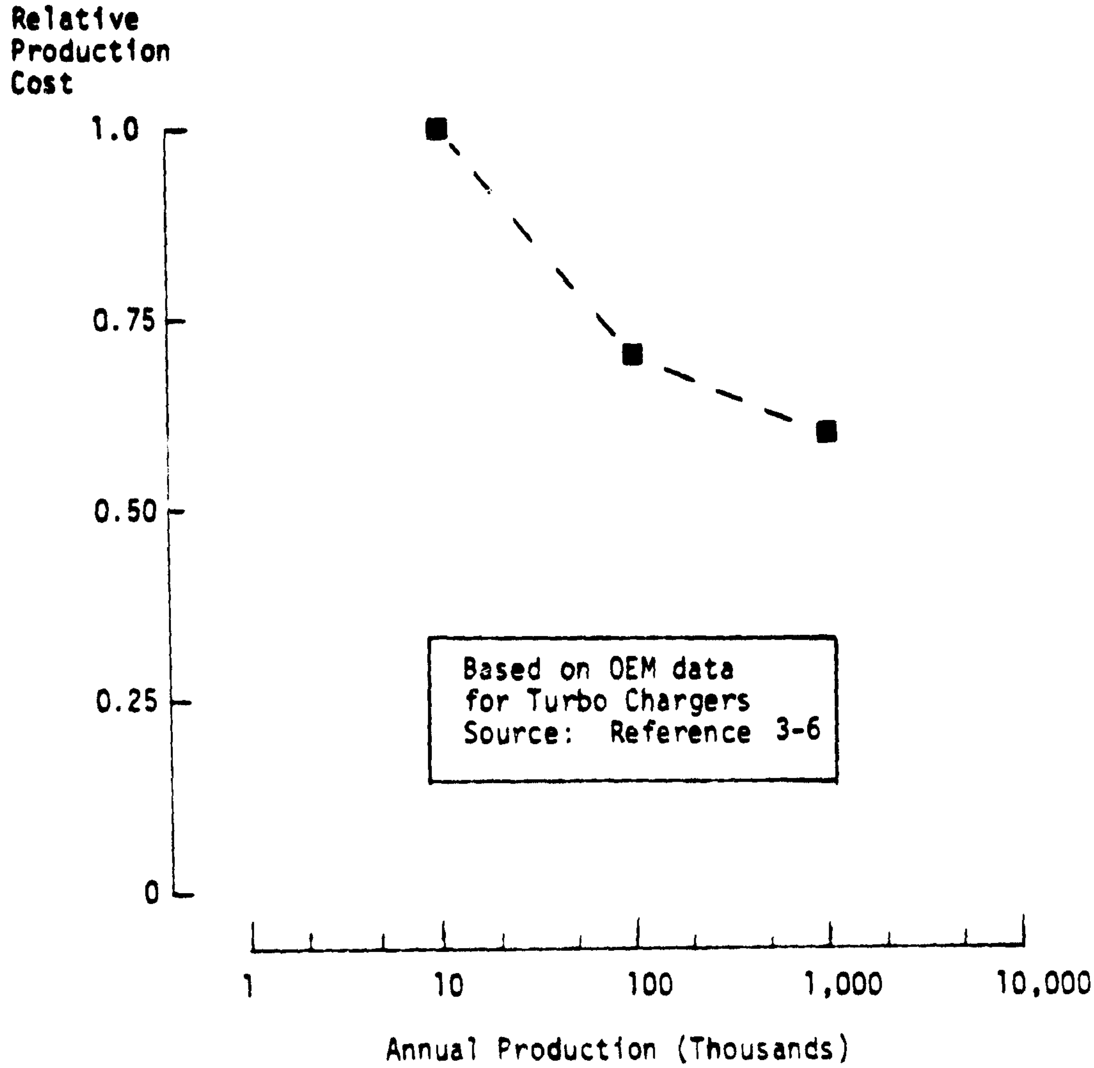


Figure 3-4. Example of Cost Reductions from Mass Production

Because appropriateness for market size is not an easily quantified factor, it will be used at the end of the evaluation process. That is, it will be one of the considerations in selecting the "best" ECS after the numerical evaluations and rankings are determined.

3.5 SOURCES OF UNCERTAINTY

Uncertainty is introduced into this evaluation by potential safety regulations, by the commercialization status of current technology, and by technological uncertainty in the electric vehicle market. The impact of these factors on the evaluation process will be discussed in this section.

3.5.1 Regulatory Uncertainty

Potential future safety standards are a source of uncertainty in evaluating alternate ECS technologies. Although, the current regulations do not generally concern themselves with ECS technologies, they have the following implications for new technologies. The regulatory procedure places specific requirements on each vehicle design, i.e., the Federal Motor Vehicle Safety Standards (Reference 3-7). However, it also requires the manufacturers to submit data on vehicle construction practices to the National Highway Traffic Safety Administration (NHTSA). If a new vehicle system proves hazardous in actual operation, NHTSA could require its recall or implement new regulations to limit its use. Thus, NHTSA is the ultimate decisionmaker of the relative safety of alternative technologies. However, since NHTSA does not act until the technology is deployed, the impact of NHTSA regulation cannot be predicted in advance. This introduces uncertainty into the validity of the rating scheme evaluation.

3.5.2 Commercialization Uncertainty

The risks of trying to introduce a new technology into an existing market are usually high. Consumers or users must perceive a strong advantage in a new alternative to justify the risk of trying it. While the electric and hybrid vehicle ECS market is not large now, several existing ECS elements exist today which could dominate the electric and hybrid vehicle market as it grows. These elements include:

- Combustion heaters
- Electric resistance heaters
- Electric air conditioners and heat pumps using the vapor compression cycle (Reference 3-3).

These ECS elements, often developed as auxiliary heating and cooling systems for "recreational vehicles", could easily be adapted for use in electric or hybrid vehicles. The existence of these technologies in commercial use can reduce the potential for commercialization of other technologies for the same purpose. However, this is not directly reflected in the development of the rating scheme. It is partially reflected in that the technologies have been subdivided by state of technical development. This type of market uncertainty is difficult to include in the rating scheme, and contributes to uncertainty in the overall results.

3.5.3 Technological Uncertainty in Electric Vehicle Market

The current study for electric vehicles is based on the assumption that near-term batteries will have limited energy density. However, considerable effort is underway to develop advanced batteries (Reference 3-8). Recently announced performance characteristics of the zinc-chlorine battery could allow practical use of battery energy to power the ECS, even if there was a large relative range penalty. The vehicle's total range, even with the ECS penalty, would be adequate for typical daily needs.

3.6 SUMMARY OF RATING SCHEME

The major elements of the rating scheme are:

- Screening out inappropriate ECS elements
- Scoring remaining ECS elements
- Selecting the "best" ECS

Separate evaluations are carried out for the electric and hybrid vehicle. A separate evaluation is made for battery heating and cooling because the battery requires only small increments on the main ECS loads. Essentially separate evaluations are carried out for ECS's in different states of development, even though the results are summarized together.

3.6.1 Screening Criteria

The screening criteria are summarized in Table 3-6. Screening is accomplished in a two step process. In the first step, each element is screened using the listed criteria. If an ECS element is acceptable by all criteria, it is retained for further evaluation. If it clearly failed to satisfy any particular criteria, it is eliminated from further consideration.

Table 3-6. Summary of Screening Criteria for ECS Elements

Cost and Performance Factors

Can the element meet basic functional requirements for system capacity?

Will system cost be excessive? (Is heater-defroster system 3 or more times current costs? Is air conditioner 2 or more times current costs?)

Impact on Vehicle Characteristics

Are system impacts excessive?

- Weight (over 300 lbs)
- Volume (over 6 cubic feet)
- Fuel requirements (over JPL guideline limits)
- Range impact (over 20% degradation)

Other performance Constraints

Does the system have potential fire or crash safety hazards?

Does the system potentially create excessive pollution, noise, or vibration?

Is the system lifetime compatible with automotive use? (3000 - 5000 hours of operation)

Is the system satisfactory from the viewpoint of reliability, repairability and controlability?

The second step of the process is reserved for cases where application of the criteria produces ambiguous results. In this case, more specific data can be gathered on this particular ECS element, as project resources allow. However, if there are already a number of attractive alternatives, the systems lacking sufficient data for evaluation will be eliminated from further consideration.

3.6.2 Scoring and Weighting

The scoring and weighting of the ECS elements is done twice in the rating scheme. The first time is an evaluation of the individual ECS elements for heating and cooling. The second time is an evaluation on an integrated ECS.

Table 3-7 summarizes the ECS rating factors, and the data required to compute the overall ECS element or integrated ECS score. Note that the weights have been normalized, so that the sum of the weights is unity. Hence, the total score is given by:

$$\text{Total Score} = \sum \text{(Rating factor score) (Weight)}$$

3.6.3 Selection of the "Best" ECS

Selection of the "best" ECS is made from the elements which rank highest in total rating score without an excessive range penalty. These elements must also be commercially available or in near-term development. Elements in mid term-development can be recommended for more extensive prototype development if they have significant potential advantages over the current ECS. The elements must also be appropriate for the expected market size. Selection of the best ECS will be documented in detail in Section 6.0 and 8.0 of the report.

Table 3-7. Summary of Scoring and Weighting Format (For systems sized to capacity in functional requirements)

Rating Factor	Source of Baseline Data	Functional Format	Weight	Comments
Cost	Cost of Current Systems	Type A	0.60	Key factor
Impact on Vehicle				
- Weight	Weight of Current Systems	Type B	0.13	
- Volume	JPL guidelines	Type B	0.13	
- Energy Use	JPL guidelines	Type B	0.14	See Note

Note: Only 0.25 Btu's of energy from petroleum fuel sources are used, on the average, to produce 1.0 Btu of charging electrical energy. This is because petroleum fuel is not the major source of utility primary energy.

For the hybrid vehicle, 1.0 Btu of electricity produced by the engine-generator combination requires 6.0 Btu of energy from the gasoline in the fuel tank. This is based on the overall efficiency of the hybrid vehicle engine-generator in producing electricity from gasoline.

4.0 DESCRIPTION OF ECS ELEMENTS

4.1 METHODOLOGY

4.1.1 Identification of ECS Elements

ECS elements were identified through a search of the literature and a construction of logical groupings for ECS technology. The two major groupings for ECS technology are energy conversion and energy storage systems.

Energy Conversion systems use a primary fuel or electrical energy to supply or remove heat from a conditioned space. Table 4-1 gives a breakdown of the major ECS energy conversion technologies identified.

Energy Storage systems, by contrast, supply heating or cooling with stored energy. The energy is stored as thermal or chemical energy and is released as needed to meet the specific loads. Table 4-2 gives a breakdown of the energy storage alternatives.

Other ECS elements were identified as being potentially important components of an integrated ECS, but did not directly fall into these two major categories. Thus, a third category, Other ECS Elements was created for these elements. Table 4-3 summarizes this subgroup.

4.1.2 Data Sources

While some ECS elements are already commercially available, many are still in the early development or conceptual stages. For those elements which are in the early development or conceptual stages, the data sources were primarily papers and proceedings from the 11th, 12th, 13th and 14th Intersociety Energy Conversion Engineering Conferences and the 4th and 5th International Symposiums on Automotive Propulsion Systems. These papers referenced additional papers (notably SAE papers) or project reports relevant to the ECS elements. Computer aided searches were used to identify data sources. The latter were obtained and reviewed. More recent information was obtained by contacting, via telephone or correspondence, those responsible for these papers or projects.

Table 4-1. Summary of Energy Conversion ECS Elements

<u>Direct Conversion</u>

Combustion Heaters
Resistance Heaters

<u>Electrically Driven Heat Pumps</u>

Electric Vapor Compression
Electric Reversed Brayton (ROVAC)
Electric Ericsson

<u>Heat Engine Driven Heat Pumps</u>

Otto (Gasoline Engine)
Vapor Compression
Otto (Gasoline Engine)
ROVAC
Stirling Vapor Compression
Ericsson Ericsson

<u>Heat Driven Heat Pumps</u>

Absorption
Hydride
Jet Compression

Table 4-2. Summary of Energy Storage ECS Elements

Thermal Energy Storage (TES)

Sensible TES Heating
Latent TES Heating
Ice Making TES Cooling
Eutectic (Phase change) TES Cooling

Chemical Energy Storage

Chemical Reaction
Intermittent Absorption
Expendible Refrigerants

Table 4-3. Summary of Other ECS Elements

Odor Control Alternatives

Charcoal Filters

Control of Solar Inputs

Reflecting Window Films
Louvered Sun Shields

Heat Recovery Systems

Ventilation Heat Recovery
(Heat Exchangers)
Waste Heat Utilization

Miscellaneous

Electrically Heated Seats
Evaporative Cooler

For those elements which are commercially available, sales brochures and manufacturers' catalogues were used to obtain element specifications on cost, performance, and physical characteristics. Again, where more recent information was sought, sales representatives and sales managers were contacted by telephone or correspondence.

Sources were compared in order to select the most understandable and informative diagrams and descriptions of the ECS elements for inclusion in the study. Where sufficient data were available, summary graphs and tables of the cost, performance, and physical characteristics of the ECS elements were compiled. See Reference 1-3.

4.1.3 Limitations of Analysis Data Base

The ECS elements description and data presentations are limited by the availability of data. This is particularly true regarding the ECS elements still in the developmental or conceptual stages. In general, descriptive analyses of these elements were available from papers or themodynamic texts. However, data on cost, performance and physical characteristics were limited. In some cases, cost, performance, and physical characteristics were proprietary. In other cases, information was presented for a specific test and in-field characteristics are expected to differ markedly. Production cost estimates for new technologies are often difficult to make. Cost estimates are highly dependent on an accurate description of the production process, which is hard to obtain for new technologies.

In general cost and performance data is available for ECS technologies already in widespread use. If data for the capacity range in question is not directly available, reasonable extrapolation of existing data can provide satisfactory estimates. By contrast, for new and emerging technologies data availability is much more limited. Data availability varied on a case by case basis.

4.1.4 Organization and Format of Summaries

Organization of the ECS element summaries in this section follows the breakdown of the elements described in Section 4.1.1. Since Reference 1-3 contains a detailed discussion of the ECS elements, only short summaries were included in this report. The key items discussed in these summaries are:

- The basic nature of the elements operation
- Key features unique to this ECS element
- Important relative merits of this ECS element

For detailed data on each ECS element, as well as a comprehensive bibliography of data sources, refer to Reference 1-3.

4.2 ENERGY CONVERSION ELEMENTS

Energy conversion ECS elements convert the energy in a liquid fuel or electricity (from the propulsion battery) to provide the desired heating or cooling service. The conversion may be direct or via a thermodynamic heat pump cycle.

Combustion heaters and mechanically (engine) driven vapor compression air conditioners are two ECS elements used extensively in automotive service. Extensive use is also made of the waste heat from the propulsion engine. However, there are a number of other technologies used for providing space heating and cooling in buildings. These include direct resistance heating, electrically driven vapor compression heat pumps and absorption heat pump cycles. In the last few years, high energy costs have encouraged research into potentially more efficient cycles such as the Stirling vapor compression and Ericsson cycles.

4.2.1 Direct Conversion Elements

Heating service can be provided by the direct combustion of liquid fuels to produce heat. Heat can also be supplied from electricity directly with a resistance heater.

Efficiencies for these direct conversion heating systems are high, usually between 70 and 100 percent. For a required heat capacity, direct conversion elements can be designed over a wide range of costs, size, and weight.

Combustion Heaters

Combustion heaters provide heat by the direct combustion of fuel. In the heater, air and fuel are mixed, ignited, and burned. The resulting hot gases circulate through a heat exchanger, transferring heat to ventilating air. The ventilating air transfers the heat to the conditioned space. Currently manufactured combustion heaters come in a wide range of sizes. They are completely self-contained, as well as being relatively small and light. Combustion heaters operate on either diesel or gasoline fuel. All data in this report is based on the use of gasoline.

For this analysis, only direct air heaters are considered. Water heating systems were considered to be too complex and heavy for use in small automobiles. (Reference 4-1)

Resistance Heaters

Resistance heaters provide heat by the direct conversion of electrical energy to heat. Heat generated in the resistors is transferred by an air stream to the conditioned space. A resistance heater system for the EHV consists of the resistance heater and a fan or blower. Efficiencies for resistance heater systems are close to 100 percent.

Resistance heaters are small, light and relatively expensive. They are very flexible and can be potentially used in a wide variety of applications. However, their requirements for electrical energy are high, which severely limits their application in vehicles. (Reference 4-2)

Distributed Resistance Heaters

Electric resistance heaters can be distributed over a specific area simply by distributing the resistive material. One possibility is the use of electroconducting films embedded in the windshield to provide defrosting and defogging service.

Electroconducting films consist of conducting materials deposited directly on glass or on a transparent plastic sheet which is then laminated into glass. These systems supply 100 to 400 watts (340-1360 Btu/hr) for a 0.72 m^2 (400 in^2) area (References 2-12 and 2-15). They are capable of providing windshield defrosting within five minutes from -18°C (0°F).

The electroconducting films have a very small size and weight impact. However, they are currently relative expensive and are primarily considered as an "optional" element.

4.2.2 Electrically Driven Heat Pumps

Heat Pumps

A heat pump is a device which can transfer heat from a cooler reservoir to a hotter one, expending energy in the process. Numerous types of heat pump systems have been devised. The broadest class is based on reversed heat engine cycles. These heat pumps require mechanical drive from either an electric motor (as discussed in this section) or a heat engine (discussed in Section 4.2.3). Other types of heat pumps based on absorption cycles or other non-mechanical drives, will be discussed in Section 4.2.4.

The heat pump has several important characteristics. First, it is the only direct means of providing a cooling effect (heat sink). Second, the heat pump itself can be reversed to provide a heating system with a coefficient of performance greater than unity. Potentially, a reversible heat pump can provide both heating and cooling capability in a single unit.

Heat pump performance is characterized by the coefficient of performance (COP), the ratio between the heating or cooling effect obtained and the required energy input. Typically, the COP and the capacity for a heat pump will decrease at very low or very high temperatures. Unfortunately, these are the same temperatures at which the heating or cooling loads are greatest. Thus, a back-up system is generally required to at least meet the maximum heating load. One exception to this general rule is the Ericsson cycle heat pump, discussed below, which retains full capacity regardless of ambient conditions. This is achieved with a variable stroke drive. The same effect can be achieved by a variable speed, constant stroke drive, which can be adapted to other heat pump cycles.

In the electrically driven heat pumps, an electric motor supplies the mechanical work input to the heat pump cycle. The following paragraphs discuss heat pump based on the vapor compression, Brayton, and Ericsson cycles.

Vapor Compression Cycle

The most common heat pump cycle is the vapor compression cycle. In this cycle, the working fluid vapor is first compressed to a high pressure gas, then condensed to a liquid. Heat from the condenser is rejected to the ambient (outside) air. The liquid refrigerant is throttled to a low pressure through an expansion valve or capillary and then allowed to evaporate, taking in heat from the conditioned space. The vapor then returns to the compressor to repeat the cycle. By reversing the roles of the condenser and evaporator, heat can also be provided to the interior space.

The electrical vapor compression cycle, using "freon" as a working fluid, is the most common heat pump system. Vapor compression heat pumps are used to provide heating and cooling in houses and larger buildings, as well as in mobile homes and recreational vehicles. It is a highly developed technology and is fairly attractive in terms of weight, size, cost, and operating performance. (Reference 4-3).

Reversed Brayton Cycle (ROVAC)

In the reversed Brayton cycle, air is the working fluid, undergoing the four basic processes of compression, heat rejection, expansion, and heat acceptance. The cycle is open with the working fluid being compressed, expanded, and circulated by a single rotary vane device. (The acronym ROVAC, from Rotary Vane Compressor is given to this system.)

The open reversed Brayton cycle is simpler than the vapor compression system because one heat exchanger is needed and sealing problems are minimal. However, the COP's for the ROVAC system are generally lower than the corresponding vapor compression cycle, requiring more energy to drive the system. Most likely a production system would be smaller and lighter than the vapor compression system, but would cost about the same to produce.

Prototype ROVAC's have been tested in automobiles (Reference 4-4). Improved ROVAC systems are still being developed and tested for automotive and stationary applications.

Ericsson Cycle

The electrically driven Ericsson heat pump is based on the reversible Ericsson cycle. The Fricsson cycle is a highly efficient regenerative gas cycle in which energy is exchanged at constant temperature between the heat source and sink. The regenerative cycle steps occur at constant pressure.

The electric Ericsson heat pump uses two linear electric motors to drive piston compressor-expanders. Regeneration is accomplished by operation of a free piston displacer/regenerator, which also aids in the transfer of the working fluid between the hot and cold heat transfer surfaces. Helium is the working fluid with freon loops used for heat transfer.

High COP's, about 90 percent of Carnot, are expected from the fully developed heat pump. Thus the system would use considerably less energy than current vapor compression systems. It is also expected to be somewhat lighter and smaller but would cost about the same in production.

One unique feature of the Ericsson cycle system is that the linear electric drive motor has a variable stroke. At larger temperature differentials, the stroke can be increased to maintain the systems capacity. Potential capacity reductions at lower temperatures could be minimized in the other cycles, if they were driven with variable speed electric motors. (References 4-5 and 4-6)

4.2.3 Heat Engine Driven Heat Pump

As an alternative to supplying mechanical work from an electric motor, a heat engine may be used to drive the heat pump. The engine cycle can be the same as the heat pump. In this evaluation four cycle combinations were studied.

Otto (Gasoline Engine) Vapor Compression and ROVAC

Both the vapor compression and ROVAC heat pumps can be driven by a small gasoline engine. Small gasoline engines have full load efficiencies of about 20 percent and are actually slightly lighter than an electric motors of the same horsepower. The cost of the gasoline engine with an electric starter will be about the same as the electric motor. Thus, the Otto (gasoline engine) driven vapor compression and ROVAC cycles are potentially attractive options available today for the ECS cooling element. (These cycles could also supply heat but probably would offer little advantage over the combustion heater.)

Stirling Vapor Compression Heat Pump

The Stirling engine driven vapor compression heat pump is a reciprocating system. The Stirling engine utilizes an efficient regenerative cycle with either helium or hydrogen as the working fluid. High temperature heat is supplied to the engine by a combustion burner and rejected via cooling air stream. The reciprocating output shaft is directly coupled to the piston of a reciprocating compressor of the standard heat pump cycle.

Several industrial programs have reported development work on the Stirling vapor compression heat pump over the last several years. The main potential advantages of this system are its high COP, due to the high efficiency of the Stirling engine. A second advantage is its capability to run directly on fossil fuel. However, systems developed to date have been primarily for residential (stationary) applications. Hence, they tend to be larger, heavier, and more expensive than systems for automotive applications. This reflects more conservative design practices needed to achieve longer operating lifetimes for residential applications. (References 4-7 and 4-8)

Ericsson Ericsson Heat Pump

The Ericsson heat pump cycle can be driven by an Ericsson engine. Coupling between the engine and heat pump is accomplished by working fluid flow between the engine and heat pump. Both cycles use helium as a working fluid and are regenerative. Heat is supplied to the Ericsson engine via a combustion burner.

The Ericsson Ericsson system is still in development. The system performance is expected to be high with overall performance in the range of 80 to 90 percent of Carnot efficiency. The overall Ericsson Ericsson heat pump system is expected to be somewhat smaller and lighter than the Otto vapor compression heat pump of equal capacity. System costs in production would be about equal. (References 4-5 and 4-6)

4.2.4 Heat Driven Heat Pumps

Heat pump cycles have been devised based on other physical principles such as the variation of solubility with temperature and pressure. The three heat pump cycles discussed here are the best known heat driven cycles.

Absorption Cycle

The absorption cycle heat pump utilizes two fluids, the refrigerant and the absorbent as the working medium. Operation is similar to the vapor compression cycle in that the high pressure refrigerant rejects heat in the condenser. After passing through the expansion valve, it absorbs heat in the evaporator at low pressure. The difference is that instead of mechanically recompressing the refrigerant to high pressure it is absorbed in the absorbent. The absorbent is pumped to a higher pressure and the refrigerant is separated from the absorbent by the addition of heat. Thus, most of the energy to drive the cycle is supplied as heat, in lieu of mechanical work.

The absorption cycle heat pump offers relatively good performance in heating, but poorer performance in cooling. It also tends to be heavy and large because a great deal of heat exchanger surface area is required. Currently, designed systems, primarily for stationary use, are considerably more costly than current electric vapor compression systems of the same capacity (References 4-9 and 4-10).

Hydride Heat Pump (HYCSOS)

The hydride heat pump is based on the absorption properties of hydrogen in different metal alloys, such as $CaNi_5 H_n$ and $LaNi_5 H_n$. These materials will absorb and reject heat as they desorb and absorb hydrogen respectively. The hydride heat pump utilizes a series of beds which alternatively exchange hydrogen while "pumping" heat. The beds also regeneratively exchange heat between themselves as part of the heat pump cycle.

Potentially, the hydride heat pump could provide performance similar to the absorption system. The hydride system would be smaller, lighter, and potentially less expensive. However, the hydride system is only in the earliest stages of conceptual development. For this study it can only be considered as a prospect for long term development (References 4-11 and 4-12).

Jet Compression Heat Pump

The jet compression heat pump is also similar to the vapor compression heat pump. A vapor jet pump replaces the mechanical compressor. Low pressure vapor is entrained in the high velocity flow stream created by a fluid (vapor) jet. The vapor is effectively "compressed" as the velocity head of the jet is recovered in a diffuser. Most of the input to the cycle is heat, which boils the working fluid to power the jet compressor.

The jet compressor heat pump system for vehicle application is presently in the conceptual stage (Reference 4-13). Data are, therefore, unavailable to describe system weight, size, cost, or actual performance. Expected advantages of the jet compressor system include size and weight advantages over the larger and heavier conventional vapor compression cycles (Reference 4-14). Also, coefficients of performance are predicted to be slightly higher than for the absorption cycle.

4.3 ENERGY STORAGE ELEMENTS

As an alternative to energy conversion, energy may be withdrawn from a previously charged energy storage subsystem. This subsystem can store the energy thermally or chemically. Thermal storage mechanism can utilize both sensible and latent heat. Chemical storage mechanisms can depend on chemical reactions, absorption properties, or release of expendable refrigerants.

4.3.1 Thermal Energy Storage

Thermal energy storage (TES) systems have been developed for both heating and cooling of buildings. The heating technology is widely utilized in Europe. This section draws on existing data for these systems.

Sensible TES Heating

Sensible heat storage is based on a technology developed in Europe for storing heat energy. It utilizes special cores, made of magnesite or cast iron, which can withstand repeated cycling to 500 -600°C (900 - 1100°F). These cores are heated by resistance heaters. The cores are enclosed in suitable insulation, so that a significant fraction of the heat may be retained for periods of 12 to 16 hours.

Potentially, these heaters provide an attractive means for storing heat energy with energy densities several times that of the propulsion battery and costs that are much lower. However, if very large amounts of heat energy are required, the sensible heat storage system becomes too large to be practical (Reference 4-15).

Latent TES Heating

Energy can also be stored in the heat of fusion associated with phase change in a eutectic material. Because of the high specific energy involved in some phase changes, latent heat storage offers the potential of even higher energy densities. Typical materials utilized are lithium, sodium and magnesium fluorides.

Potential energy densities are twice that of sensible heat storage, although costs are much higher. Latent heat storage technology is currently in the development phase (References 4-15 and 4-16).

Ice Making TES Cooling

In the same manner that certain materials can store heat, ice has long been used as a stored heat sink. Ice making cooling utilizes a standard vapor compression refrigeration unit to make the ice. The ice is retained in an insulated container to serve as a sink for heat for the ventilation air. A separate water heat exchange loop transfers the heat to the ice.

An ice making storage system could potentially supply a limited amount of cooling capacity for a vehicle. The system's size, weight, and cost will be proportional to the amount of capacity requi [illegible] erence 4-15).

Eutectic TES Cooling

Other eutectic materials, such as certair [illegible] hydrates, can provide considerable thermal storage capacity for cooling. Eutectic materials would provide for a more efficient storage system since their transition temperature is higher, 13°C (55°F) instead of 0°C (32°F). However, their costs are higher and their energy storage density is lower than that for ice (Reference 4-15).

Thermal Energy Storage for Long Durations

All thermal energy storage systems suffer from a common drawback. While the thermal storage device can be insulated, some energy will leak out. The thermal energy store has a typical self-discharge period of several days. For a vehicle where use patterns are often intermittent, this can cause practical problems. If the vehicle is idle for long periods, the store must be recharged or the ECS will not function. Special requirements like this may not find wide market acceptance by vehicle users.

4.3.2 Chemical Energy Storage

Chemical energy storage systems are based on chemical reactions, absorption or use of expendable refrigerant.

Chemical Reactions

There are a number of reversible chemical reactions being studied as energy storage mechanisms. A typical reaction considered involves use of paired ammoniated salts. At high temperature, the ammoniated salts decompose into ammonia (NH_3) gas and the salt. Heat is absorbed in this process. The ammonia reacts with a second salt at a lower temperature, releasing heat. When the process is reversed, heat is absorbed by the second salt at low temperature, providing a cooling effect.

It is estimated that this particular chemical reaction system would cost about the same as a conventional cooling system, if its operating time was limited to 2 or 3 hours. However, the current versions of the system are much too large and heavy for automotive application. (References 4-17 and 4-18)

Intermittent Absorption

The intermittent absorption system is based on having a single charge of refrigerant dissolved in an absorbent. The two are separated by adding heat to the mixture and recondensing the refrigerant in a separate container. Upon reevaporation of the refrigerant and its subsequent absorption, heat is "pumped" from the low temperature to high temperature. This continues until all the refrigerant is absorbed.

C-2

Prototype and potential systems involve combinations such as:

- Water and magnesium chloride hydrate
- Lithium bromide and water
- Dimethyl glycol and freon (R-22)
- Water and ammonia

Preliminary estimates for intermittent absorption systems indicate their size, weight and cost will probably be excessive for vehicle applications. (References 4-17 and 4-19)

Expendable Refrigerants

A third alternative for chemical energy storage is expendable refrigerants. Three "traditional" expendible refrigerants were examined. Liquid nitrogen and its associated tankage were clearly too heavy for automotive use. Ice and dry ice were possibilities, though the weights required were high and they were inconvenient for the vehicle user. Expendible refrigerants also would not be economically practical because they are not widely available at a price that would be attractive to the vehicle owner. (Reference 4-20).

4.4 OTHER ECS ELEMENTS

4.4.1 Odor Control

Activated charcoal filters can be used to reduce the requirement for ventilation air by absorbing odors onto the filter bed material. Ventilation air is continuously recirculated through the filter bed with make-up (fresh) air only 15 to 30 percent of the ventilation flow.

About 1 to 2 pounds of activated charcoal is needed per person per year in typical building ventilation applications. Intermittent service such as automobile operation could extend this by a factor of 2 or 3. Hence, a small inexpensive filter with about a pound of charcoal would serve about a year in a vehicle. The filter would be replaced or the carbon regenerated.

The benefits of the charcoal filter are high. Reduced ventilation load significantly reduces ECS capacity requirements (about 50%). Hence, significant savings can be achieved in system size, weight, cost, and energy requirements (Reference 4-21).

4.4.2 Control of Solar Radiation Input

Several techniques are available for controlling solar radiation inputs through the vehicles windows. The two techniques investigated in this study are reflective films and louvered sun shields.

Reflecting Window Films

A variety of "Mylar" based reflective films are available which can reduce the radiant heat load up to 80 percent. Their costs are very low (Reference 3-3). However, use of these films is restricted by the requirements for visible light transmission in the windshield and side windows. Tinted windows also reduce the radiant heat load, but they are limited in terms of the heat reduction they can provide. Effectively, the radiant heat load can only be reduced by about 35% (Reference 1-1). However, even this level of solar control is highly effective in reducing the ECS capacity requirements.

Louvered Sun Shields

Louvered sun shields for rear windows are an alternate approach to reducing solar loads on the rear window. They are made of plastic or aluminum. Although their costs are higher than reflecting films, they can make an effective contribution in reducing the cooling system capacity. Properly designed louvers will have a minimal impact on the vehicles aerodynamic characteristics. They are estimated to reduce the radiant heat load by 80 percent (Reference 1-1).

4.4.3 Heat Recovery Systems

Heat recovery can be used in the ECS in two ways. First, heat can be recovered from the ventilation exhaust from the passenger compartment and used to condition incoming ventilation air. Second, waste heat from the vehicles main propulsion system can be recovered and used to supplement the ECS's heat inputs.

Ventilation Heat Recovery

Ventilation heat losses can be reduced up to 70% by passing ventilation air through a counterflow heat exchanger. Exhaust air can be used to condition incoming air in either the heating and cooling mode. Paper plate and fin heat exchangers are the lowest cost, highest effectiveness and most compact method of heat recovery. However, use of heat recovery is much more expensive than restricting the ventilation flow and recirculating the air through a charcoal filter for odor control. (References 1-1 and 4-22)

Waste Heat Recovery

Considerable amounts of waste heat are potentially available from the vehicle propulsion system. In the electric vehicle, normal operation ('D' cycles) can supply up to half the vehicle's heating load from motor and controller waste heat. Since the motor and controller are often air cooled, the heated cooling air could be used as input to the ventilation air stream. Care would be needed not to introduce contaminants such as ozone from arcing brushes into the passenger compartment. (Reference 4-23)

Very large quantities of waste heat are available from the hybrid vehicle power system, especially from the heat engine. Essentially all of the ECS heat requirements can be met once the heat engine starts to operate. Sufficient waste heat is available to drive the heat driven heat pump cycles. The cost of recovering this waste heat is low enough to make this an attractive option (References 1-3 and 4-24).

4.4.4 Special ECS Elements

Electrically Heated Seats

Electrically heated seats are used in a few vehicles to supplement the normal heating system during warm-up and very cold conditions. The electric seat supplements the normal metabolic heat rate, to produce the sensation of comfort in a cold environment. Electric seats were not found to be particularly effective in producing "comfort" and probably not a cost effective ECS optior (Reference 1-3).

Evaporative Cooling

An evaporative cooler functions by adding moisture adiabatically to an air stream. This reduces the dry bulb temperature. However, under the design ambient conditions used in this study, an evaporative cooler can not provide the desired interior conditions within the "comfort zone". Hence, the evaporative cooler can not replace the heat pump system in cooling service (Reference 1-3).

4.5 DATA SUMMARY OF ECS ELEMENTS

Extensive quantitative data was developed on the ECS elements in Reference 1-3. In this section, a series of individual tables is presented to summarize the data for all ECS elements. The EC^e elements are sized for the design range capacity. Element cnaracterist are given at the high and low end of this range. Energy storage systems are sized with sufficient capacity to operate at maximum capacity for 2.5 hours, about the duration of the propulsion battery when driving "D" cycles.

The various ECS elements are summarized in the following tables:

Table 4-4. Summary of Characteristics of Energy Conversion ECS Elements

Table 4-5. Summary of Characteristics of Energy Storage ECS Elements

Table 4-6. Summary of Characteristics of Other ECS Elements

These tables follow on the succeeding pages.

Table 4-4a. Summary of Characteristics of Energy Conversion ECS Elements

Element: Combustion Heater

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	RANGE OF VALUES HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	N/A	N/A
	Btu/hr	N/A	N/A
INITIAL COST:	Dollars	200	250
WEIGHT:	kg	5.5	8.2
	lb	12	18
VOLUME:	m^3	0.017	0.020
	ft^3	0.6	0.7
ENERGY REQUIREMENT HEATING:	watt	2,855	3,617
	Btu/hr	9,740	12,340
COOLING:	watt	--	--
	Btu/hr	--	--
FUEL TYPE: Gasoline			
RANGE IMPACT:	Percent	Neg	Neg

DEVELOPMENT STATUS: Near-Term

COMMENTS: Commercially Available - Already used in many EVs.

Table 4-4b. Summary of Characteristics of Energy Conversion ECS Elements

Element: Resistance Heater

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	N/A	N/A
	Btu/hr	N/A	N/A
INITIAL COST:	Dollars	50	60
WEIGHT:	kg	6.8	8.3
	lb	15	18
VOLUME:	m^3	0.020	0.028
	ft^3	0.7	1.0
ENERGY REQUIREMENT			
HEATING:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING:	watt	--	--
	Btu/hr	--	--

FUEL TYPE: Electricity

RANGE IMPACT:	Percent	30	46

DEVELOPMENT STATUS: Near-Term

COMMENTS:

Table 4-4c. Summary of Characteristics of Energy Conversion ECS Elements

Element: Electric Vapor Compression

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	3,224	4,103
	Btu/hr	11,000	14,000
INITIAL COST:	Dollars	600	750
WEIGHT:	kg	54	77
	lb	120	170
VOLUME:	m^3	0.10	0.11
	ft^3	3.5	4.0
ENERGY REQUIREMENT HEATING:	watt	935	1,184
	Btu/hr	3,190	4,040
COOLING:	watt	1,536	19,515
	Btu/hr	5,240	6,670

FUEL TYPE: Electricity

RANGE IMPACT:	Percent	26	34

DEVELOPMENT STATUS: Near-Term

COMMENTS: Commercially available and widely used for building space conditioning.

Table 4-4d. Summary of Characteristics of Energy Conversion ECS Elements

Element: Electric Reverse Brayton (ROVAC)

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	3,224	4,103
	Btu/hr	11,000	14,000
INITIAL COST:	Dollars	470	490
WEIGHT:	kg	50	61
	lb	110	120
VOLUME:	m^3	0.040	0.048
	ft^3	1.4	1.6
ENERGY REQUIREMENT			
HEATING:	watt	917	1,160
	Btu/hr	2,900	3,650
COOLING:	watt	2,304	2,931
	Btu/hr	6,900	8,750

FUEL TYPE: Electricity

RANGE IMPACT:	Percent	33	47

DEVELOPMENT STATUS: Near-Term

COMMENTS: Prototypes tested in automobile with mechanical drive.

Table 4-4e. Summary of Characteristics of Energy Conversion ECS Elements

Element: Electric Ericsson

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	3,224	4,103
	Btu/hr	11,000	14,000
INITIAL COST:	Dollars	600	750
WEIGHT:	kg	25	30
	lb	55	65
VOLUME:	m^3	0.040	0.051
	ft^3	1.4	1.8
ENERGY REQUIREMENT			
HEATING:	watt	999	1,266
	Btu/hr	3,410	4,320
COOLING:	watt	1,342	1,709
	Btu/hr	4,580	5,830

FUEL TYPE: Electricity

RANGE IMPACT:	Percent	21	27

DEVELOPMENT STATUS: Mid-Term

COMMENTS: Laboratory prototypes being designed and tested.

Table 4-4f. Summary of Characteristics of Energy Conversion ECS Elements

Element: Stirling Vapor Compression

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	3,224	4,103
	Btu/hr	11,000	14,000
INITIAL COST:	Dollars	1,100	1,200
WEIGHT:	kg	77	98
	lb	170	215
VOLUME:	m^3	0.24	0.28
	ft^3	8.5	10
ENERGY REQUIREMENT			
HEATING:	watt	1,292	1,638
	Btu/hr	4,410	5,590
COOLING:	watt	3,394	4,308
	Btu/hr	11,580	14,700

FUEL TYPE: Gasoline

RANGE IMPACT:	Percent	6	8

DEVELOPMENT STATUS: Mid-Term

COMMENTS: Prototype units undergoing experimental evaluation

Table 4-4g. Summary of Characteristics of Energy Conversion ECS Elements

Element: Ericsson Ericsson

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	3,224	4,103
	Btu/hr	11,000	14,000
INITIAL COST:	Dollars	600	750
WEIGHT:	kg	27	32
	lb	60	70
VOLUME:	m^3	0.057	0.065
	ft^3	2.0	2.3
ENERGY REQUIREMENT HEATING:	watt	1,046	1,328
	Btu/hr	3,570	4,520
COOLING:	watt	1,401	1,785
	Btu/hr	4,780	6,090

FUEL TYPE: Gasoline

RANGE IMPACT:	Percent	2	2

DEVELOPMENT STATUS: Mid-Term

COMMENTS: Laboratory prototypes being designed and tested

Table 4-4h. Summary of Characteristics of Energy Conversion ECS Elements

Element: Otto (Gasoline Engine) Vapor Compression

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	3,224	4,103
	Btu/hr	11,000	14,000
INITIAL COST:	Dollars	580	720
WEIGHT:	kg	41	64
	lb	90	140
VOLUME:	m^3	0.11	0.13
	ft^3	4.0	4.5
ENERGY REQUIREMENT			
HEATING:	watt	4,226	5,355
	Btu/hr	14,420	18,270
COOLING:	watt	6,858	8,731
	Btu/hr	23,400	29,790

FUEL TYPE: Gasoline

RANGE IMPACT:	Percent	3	5

DEVELOPMENT STATUS: Near-Term

COMMENTS: Used for cooling only

Table 4-41. Summary of Characteristics of Energy Conversion ECS Elements

Element: Otto (Gasoline Engine) ROVAC

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	3,224	4,103
	Btu/hr	11,000	14,000
INITIAL COST:	Dollars	440	465
WEIGHT:	kg	36	41
	lb	80	90
VOLUME:	m^3	0.056	0.071
	ft^3	2.0	2.5
ENERGY REQUIREMENT			
HEATING:	watt	4,147	5,252
	Btu/hr	13,000	16,400
COOLING:	watt	10,404	13,236
	Btu/hr	31,400	40,000

FUEL TYPE: Gasoline

RANGE IMPACT:	Percent	2	3

DEVELOPMENT STATUS: Near-Term

COMMENTS: Prototype ROVAC (Mechanically driven) tested in car - Used for cooling only.

Table 4-4j. Summary of Characteristics of Energy Conversion ECS Elements

Element: Absorption

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	RANGE OF VALUES HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	3,224	4,103
	Btu/hr	11,000	14,000
INITIAL COST:	Dollars	1,010	1,280
WEIGHT:	kg	95	118
	lb	210	260
VOLUME:	m^3	0.28	0.34
	ft^3	10	12
ENERGY REQUIREMENT			
HEATING:	watt	1,832	2,321
	Btu/hr	6,250	7,920
COOLING:	watt	6,448	8,206
	Btu/hr	22,000	28,000

FUEL TYPE: Gasoline

RANGE IMPACT:	Percent	7	9

DEVELOPMENT STATUS: Mid-Term

COMMENTS:

Table 4-4k. Summary of Characteristics of Energy Conversion ECS Elements

Element: Hydride

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	3,224	4,103
	Btu/hr	11,000	14,000
INITIAL COST:	Dollars	1,100	1,400
WEIGHT:	kg	55	68
	lb	120	150
VOLUME:	m^3	0.14	0.17
	ft^3	5.0	6.0
ENERGY REQUIREMENT			
HEATING:	watt	1,099	1,392
	Btu/hr	3,750	4,750
COOLING:	watt	3,224	4,103
	Btu/hr	11,000	14,000

FUEL TYPE: Gasoline

RANGE IMPACT:	Percent	4	5

DEVELOPMENT STATUS: Long-Term

COMMENTS: Still in conceptual stage

Table 4-41. Summary of Characteristics of Energy Conversion ECS Elements

Element: Jet Compression

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt	2,198	2,784
	Btu/hr	7,500	9,500
COOLING CAPACITY:	watt	3,224	4,103
	Btu/hr	11,000	14,000
INITIAL COST:	Dollars	--	--
WEIGHT:	kg	--	--
	lb	--	--
VOLUME:	m^3	--	--
	ft^3	--	--
ENERGY REQUIREMENT			
HEATING:	watt	1,377	1,741
	Btu/hr	4,700	5,940
COOLING:	watt	5,363	6,829
	Btu/hr	18,300	23,300

FUEL TYPE: Gasoline

RANGE IMPACT:	Percent	--	--

DEVELOPMENT STATUS: Long-Term

COMMENTS: Specific data on characteristics not available.

Table 4-4. Summary of Characteristics of Energy Conversion ECS Elements

Key to Tables

N/A - Not applicable.

Note:

Range impact is for electric vehicles. See Section 5.2. Impacts for hybrid vehicles are similar.

Table 4-5a. Summary of Characteristics of Energy Storage ECS Elements.

Element: Sensible TES Heating

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt-hr	5,495	6,961
	Btu	18,750	23,750
COOLING CAPACITY:	watt-hr	N/A	N/A
	Btu	N/A	N/A
INITIAL COST:	Dollars	60	90
WEIGHT:	kg	57	79
	lb	125	175
VOLUME:	m^3	0.037	0.056
	ft^3	1.3	2.0
ENERGY REQUIREMENT			
HEATING:	watt-hr	6,465	8,189
	Btu	22,060	27,940
COOLING:	watt	N/A	N/A
	Btu	N/A	N/A

FUEL TYPE: Charging Electricity

RANGE IMPACT:	Percent	3	5

DEVELOPMENT STATUS: Near-Term

COMMENTS: Widely used for residential heating in Europe.

Table 4-5b. Summary of Characteristics of Energy Storage ECS Elements.

Element: Latent TES Heating

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt-hr	5,495	6,961
	Btu	18,750	23,750
COOLING CAPACITY:	watt -hr	N/A	N/A
	Btu	N/A	N/A
INITIAL COST:	Dollars	225	315
WEIGHT:	kg	23	32
	lb	50	70
VOLUME:	m^3	0.014	0.020
	ft^3	0.5	0.7
ENERGY REQUIREMENT			
HEATING:	watt-hr	6,465	8,189
	Btu	22,060	27,940
COOLING:	watt-hr	N/A	N/A
	Btu	N/A	N/A

FUEL TYPE: Charging Electricity

RANGE IMPACT:	Percent	1	2

DEVELOPMENT STATUS: Mid-Term

COMMENTS:

Table 4-5c. Summary of Characteristics of Energy Storage ECS Elements.

Element: Icemaking TES Cooling

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	RANGE OF VALUES HIGH
HEATING CAPACITY:	watt-hr	N/A	N/A
	Btu	N/A	N/A
COOLING CAPACITY:	watt-hr	8,060	10,258
	Btu	27,500	35,000
INITIAL COST:	Dollars	525	615
WEIGHT:	kg	123	150
	lb	270	330
VOLUME:	m^3	0.12	0.16
	ft^3	4.2	5.6
ENERGY REQUIREMENT			
HEATING:	watt-hr	N/A	N/A
	Btu	N/A	N/A
COOLING:	watt-hr	8,939	11,401
	Btu	30,500	38,900
FUEL TYPE: Charging Electricity			
RANGE IMPACT:	Percent	8	10
DEVELOPMENT STATUS: Near-Term			

COMMENTS: Cost includes charging refrigeration system.

Table 4-5d. Summary of Characteristics of Energy Storage ECS Elements.

Element: Eutectic TES Cooling

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt-hr	N/A	N/A
	Btu	N/A	N/A
COOLING CAPACITY:	watt-hr	8,060	10,258
	Btu	27,500	35,000
INITIAL COST:	Dollars	540	630
WEIGHT:	kg	191	241
	lb	420	530
VOLUME:	m^3	0.13	0.17
	ft^3	4.7	6.0
ENERGY REQUIREMENT			
HEATING:	watt-hr	N/A	N/A
	Btu	N/A	N/A
COOLING:	watt-hr	8,939	11,401
	Btu	30,500	38,900
FUEL TYPE: Charging Electricity			
RANGE IMPACT:	Percent	12	15

DEVELOPMENT STATUS: Mid-Term

COMMENTS: Cost includes charging refrigeration system.

Table 4-5e. Summary of Characteristics of Energy Storage ECS Elements.

Element: Chemical Reaction

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt-hr	5,495	6,961
	Btu	18,750	23,750
COOLING CAPACITY:	watt-hr	8,060	10,258
	Btu	27,500	35,000
INITIAL COST:	Dollars	690	870
WEIGHT:	kg	209	263
	lb	460	580
VOLUME:	m^3	0.18	0.23
	ft^3	6.2	8.0
ENERGY REQUIREMENT			
HEATING:	watt-hr	6,096	7,734
	Btu	20,800	26,390
COOLING:	watt-hr	8,939	11,401
	Btu	30,500	38,900

FUEL TYPE: Charging Electricity or Fuel

RANGE IMPACT:	Percent	13	17

DEVELOPMENT STATUS: Long-Term

COMMENTS: Cost includes charging system

Table 4-5f. Summary of Characteristics of Energy Storage ECS Elements.

Element: Intermittent Absorption

CHARACTERISTIC	UNITS	RANGE OF VALUES LOW	HIGH
HEATING CAPACITY:	watt-hr	5,495	6,961
	Btu	18,750	23,750
COOLING CAPACITY:	watt-hr	8,060	10,258
	Btu	27,500	35,000
INITIAL COST:	Dollars	1,350	1,700
WEIGHT:	kg	93	118
	lb	205	260
VOLUME:	m^3	--	--
	ft^3	--	--
ENERGY REQUIREMENT			
HEATING:	watt-hr	6,096	7,734
	Btu	20,800	26,390
COOLING:	watt-hr	8,939	11,401
	Btu	30,500	38,900

FUEL TYPE: Charging Electricity or Fuel

RANGE IMPACT:	Percent	--	--

DEVELOPMENT STATUS: Long-Term

COMMENTS: Cost includes charging system

Table 4-5. Summary of Characteristics of Energy Storage ECS Elements

Key to Tables

N/A - Not applicable

Notes to Table

Charging unit cost is based to an 8 hour charge period with an electrical vapor compression cycle heat pump. Where charging fuel is also indicated, a combustion heater can supply the charging heat.

The range impact is for electric vehicles - Impacts for hybrid vehicles are similar.

Table 4-6a. Summary of Characteristics of Other ECS Elements

Element: Charcoal Filter

PURPOSE:

Odor control with recirculating air system

CHARACTERISTICS	UNITS	VALUE
INITIAL COSTS:	Dollars	10
WEIGHT:	kg	0.5
	lb	1
VOLUME:	m^3	Neg
	ft^3	Neg

COMMENTS: Will require annual replacement.

Table 4-6b. Summary of Characteristics of Other ECS Elements

Element: Reflecting Window Films

PURPOSE:

To reduce solar radiation load through windows.

CHARACTERISTICS	UNITS	VALUE
INITIAL COSTS:	Dollars	6
WEIGHT:	kg	Neg
	lb	Neg
VOLUME:	m^3	Neg
	ft^3	Neg

COMMENTS: Tinting on windows reduce heat load 35%. Reflective films on windows can reduce heat load 80%, but use is limited by Federal Motor Vehicle Safety Standards.

Table 4-6c. Summary of Characteristics of Other ECS Elements

Element: Louvered Sun Shield

PURPOSE:

To reduce solar radiation load through rear window.

CHARACTERISTICS	UNITS	VALUE
INITIAL COSTS:	Dollars	50
WEIGHT:	kg	3.2
	lb	7
VOLUME:	m^3	N/A
	ft^3	N/A

COMMENTS: May produce a slight increase (2 to 3 percent) in C_DA. Estimated to reduce solar radiation load 80%. Weight is for plastic version.

Table 4-6d. Summary of Characteristics of Other ECS Elements

Element: Ventilation Heat Recovery

PURPOSE:

Heat exchanger to recover heat from ventilation exhaust air.

CHARACTERISTICS	UNITS	VALUE
INITIAL COSTS:	Dollars	200
WEIGHT:	kg	9.1
	lb	20
VOLUME:	m^3	0.042
	ft^3	1.5

COMMENTS: Based on paper plate and fin heat exchangers. Designed to recover 70 percent of ventilation heat load.

5.0 ELIMINATION OF INAPPROPRIATE ECS ELEMENTS

5.1 METHODOLOGY

5.1.1 Outline of Method

The ECS elements which will be selected as "best" for the electric and hybrid vehicle (EHV) application must meet the functional requirements and other criteria defined in Chapters 2.0 and 3.0. In particular, it must meet the requirements and criteria summarized in Tables 2-13 and 3-2. Each of these elements was summarized in Chapter 4.0. Detailed data on the principles of operation, cost, performance, and physical characteristics of the elements is available in Reference 1-3. This data will be the basis of the screening process.

In this chapter each of the systems described in Chapter 4.0 is evaluated in comparison to a baseline environmental control subsystem. This baseline system, which meets all functional requirements and other criteria, is described in detail in Section 5.2. Limits of acceptable deviation from the baseline requirements are also presented. The systems which deviate excessively from the baseline requirements are deemed inappropriate for the electric vehicle and are eliminated from further study. However, where indicated, they may be considered again for the hydrid vehicle ECS evaluation in Section 8.0

Format of Presentation

The discussion of the elimination of inappropriate ECS elements is organized in the following manner. First, the basis of the elimination is described by defining a baseline ECS element which satisfies all of the functional requirements and meets all other criteria for adaptation in the electric and hybrid vehicle. Second, all of the ECS elements are compared to the baseline element. (The results of this comparison are summarized in tabular form in Reference 1-4.) Finally, those elements which do not meet the functional requirements or which excessively impact the design and performance of the EHV are eliminated from further study. The reasons for elimimation of each element deemed inappropriate are discussed and summarized.

5.1.2 Limitations of Analysis

In some cases, it was difficult to accurately assess whether an ECS element met specific criteria. Also, minor variations in design can improve system lifetime or change noise levels or operating emissions. The focus of this report is on the elimination of those ECS elements which possess qualities detrimental to the EHV, those which cannot be overcome by minor design changes. ECS systems failing to meet any one criteria by a substantial margin or several criteria by narrower margins are not eliminated if the deficiencies could be remedied through further research and development. Some criteria are specifically noted as being only applied to electric or hybrid vehicles.

5.2 DEFINITION OF BASELINE REQUIREMENTS

The elimination of inappropriate ECS elements requires that all elements be compared on an equal basis. The following discussion describes requirements for an element which satisfies all functional requirements, remains within the limits of vehicle design and operational impact, and meets appropriate safety and emissions standards.

5.2.1 Functional Requirements

The functional requirements for the ECS element include heating and cooling capacity, response time (the time required to reach capacity), battery temperature control, windscreen defrosting and defogging, and control flexibility. Specific baseline values for these requirements are given below.

Capacity - The calculated capacity of the ECS is 5.6 kW (19,000 Btu/hr) for heating, and 7.5 kW (25,500 Btu/hr) for cooling, assuming there are four passengers in the vehicle. The heating requirement was based on an outdoor temperature of -29°C (-20°F). The cooling requirement was based on an outdoor temperature of 49°C (120°F). These capacity levels are based on full ventilation flow.

However, if the vehicle is designed with a controlled ventilation system, the net ventilation flow (make-up air) will be between 43 to 77 m^3/hr (25 to 45 cfm). At these ventilation levels, the range of required capacities are as follows:

Heating: 2.2 to 2.8 kW (7,500 to 9,500 Btu/hr)

Cooling: 3.2 to 4.1 kW (11,000 to 14,000 Btu/hr)

These values will be referred to as the design range. No credit has been taken for the waste heat available to supplement these levels. All parameters of the ECS will be calculated for both the high and low values of the design range.

Total Stored Energy to Recover From "Cold Soak" - For vehicles having storage heating systems, the heating system should have the capacity to recover the battery from the "cold soak" condition at -29°C (-20°F). This requirement is in addition to the basic requirement for the ECS to supply the maximum heating load on the maximum range mission. The two requirements mean the total energy stored by the system is as follows:

Requirement (worst case)	Required Energy
Maximum capacity level for maximum range with minimum ventilation load	5,495 W-hr (18,750 Btu)
Energy to recover battery from "cold soak"	7,034 W-hr (24,000 Btu)
Total heating system required storage capacity	12,529 W-hr (42,750 Btu)

Response Time - The required time to reach heating capacity is less than 10 minutes. Time to capacity for the cooling element is less than 3 minutes with a 10 minute period to produce comfort for front seat passengers.

Windshield Defrosting & Defogging - Federal Motor Vehicle Safety Standard 103 (FMVSS 103) requires all vehicles to have a windshield defrosting and defogging system. The nominal capacity of the windshield defroster must be 3.4 kW (11,500 Btu/hr) with an air flow rate of 340 m^3/hr (200 cfm). This capacity is reduced by recirculation of passenger compartment air in the defroster. Thus, the heating ECS serves as the defroster, as in current vehicle practice. An optional embedded windshield heater could also be used as the defroster. The required capacity of the embedded heater is 0.6 kW.

Battery Temperature Control - The battery controller must maintain battery temperature in the 49°C ± 6°C (120°F ± 10°F) temperature range for optimum effectiveness. This requires the heating capacity of the temperature controller to be 380 watts (1,300 Btu/hr), when the battery compartment has 2.5 cm (1.0 in) of mineral fiber insulation. This requirement is considered within the range of the heating ECS unit. Battery cooling is accomplished by means of outside air passed over the battery by a small 120 m^3/hr (70 cfm) fan. If lower battery temperatures are allowed, then less supplemental heat is required for battery temperature control.

5.2.2 Impacts on Vehicle System

The impacts of any one element on the vehicle design and operation are defined in terms of cost, weight, volume, energy requirement, and reduction in range.

Cost - The baseline cost is taken as the cost of heating and cooling systems presently used in automobiles. The cost of a typical automobile heater is about \$85. A typical air conditioner cost is \$470 (Table 3-3). The complete heating and air conditioning system cost would be \$555. The cost of the ECS element selected should not be greater than 2.5 times the cost for the total ECS. Thus the final cost should not be greater than \$1388. Since the relative cost of the heater is much lower than the air conditioner and the air conditioner is an "option," the vehicle owner will be more sensitive to the cost of the air conditioner.

Weight - The weight of an ECS element should not exceed about three times the current, or baseline weight. Current automobile air conditioning systems weigh approximately 45 kg (100 lbs) (Reference 5-1). Current heating systems weigh approximately 9 kg (20 lbs) (Reference 5-2). Element weights up to 136 kg (300 lbs) will be acceptable.

Volume - The ECS element volume should be less than 0.17 m^3 (6 ft^3) (Reference 1-5). This is taken as the baseline value.

Energy Requirements - Energy requirements were tabulated, but not used in the elimination of inappropriate ECS elements.

Range Impact

Vehicle range impact, $\Delta R/R$ is given by JPL (Reference 1-5) as:

$$\Delta R/R = -(.046/ft^2)\ \Delta(C_DA) - (.00026/lb)\ \Delta M - (.147/kW)\ \Delta P$$

where $\Delta(C_DA)$ is the change in product of aerodynamic drag coefficient and vehicle cross-section area due to the ECS, ΔM is the change in vehicle mass due to the ECS, and ΔP is the average electrical energy required by the ECS, not including energy derivable from onboard fuel. The average energy required by the ECS accounts for the systems efficiency or coefficient of performance in meeting the required capacity. Because the drag coefficient remains essentially constant, $\Delta(C_DA)$ can be replaced by $\Delta A\ C_D$, the change in cross-sectional area.

An approximation for the relation between the vehicle cross-sectional area is given by $V = A^{3/2}$. The volume change is then related to the area change by:

$$dV = \frac{3}{2} A^{1/2}\ dA$$

Dividing both sides by V and rearranging gives:

$$dA = \frac{2}{3}\frac{A}{V}\ dV$$

Assuming a typical vehicle cross sectional area of 1.9 m^2 (20 ft^2) and a typical vehicle volume of 8.7 m^3 (307 ft^3), based on data for a near-term electric vehicle (References 2-13 and 5-3), the relation becomes:

$$dA = 0.043\ dV$$

Substituting this relation into the range impact equation gives a relation based on volume change, rather than area change:

$$\Delta R/R = (-.0020/ft^3)\ \Delta VC_D - (.00026/lb)\ \Delta M - (.147/kW)\ \Delta P$$

where ΔV is the change in volume due to the ECS element.

It is realized that this approximation is very limited. Volume requirements are usually met by making vehicles longer and "box-like." Requirements for a larger vehicle may in turn add additional weight which may not be fully accounted for by the range equation. The range impact of the ECS elements were evaluated using the modified JPL equations. The ECS element should not decrease the vehicle range by more than 20 percent.

5.2.3 Other Criteria

Developmental Status - In order to be considered in this evaluation elements must be commercially available, or in near or mid-term development (see definitions in Table 3-4).

Safety and Emissions - Any element which could be exceptionally hazardous in a crash or fire was considered for elimination. Elements with potentially excessive emissions were also evaluated.

Lifetime - Normal vehicle lifetime was considered to be 3000 to 5000 operating hours. Systems which could not meet this lifetime requirement were eliminated.

Noise and Vibration - Noise and vibration are usually dependent on detailed system design. Systems which could not be made acceptable in terms of noise and vibrations were eliminated.

Serviceability - Systems with unusual or excessive service requirements were eliminated.

5.3 SUMMARY OF INAPPROPRIATE ECS ELEMENTS

The elements which were eliminated from the detailed selection process of the "best" ECS elements for the electric vehicle are summarized below. Those elements which may still be applicable to the hybrid vehicle are indicated. The reasons for the elimination are also presented.

Resistance Heater

In all cases the decrease in electric vehicle range for this element is excessive. The direct electrical requirement from the battery can reduce the range by 30 to 46 percent. However, this element is potentially applicable to the hybrid vehicle.

Electric Vapor Compression Heat Pump

In all cases the impact of this element on the vehicle range exceeds acceptable limits. The range reduction is between 26 and 34 percent. However, this element is potentially applicable to hybrid vehicles.

Electric Reversed Brayton Cycle (ROVAC) Heat Pump

The range reduction for this element is excessive for the electric vehicle application. The direct electrical energy requirements from the battery can reduce the range from 37 to 47 percent. However, this element is potentially applicable to the hybrid vehicle.

Electric Ericsson Cycle

The range reduction for this element is excessive for the electric vehicle application. The direct electrical energy requirements from the battery can reduce the range from 21 to 27 percent. However, this element is potentially applicable to the hybrid vehicle.

Sensible TES Heating

When the nominal storage capacity of this system includes the capacity to recover from "cold soak", the weight of this element is 315 lbs., which is excessive.

Latent TES Heating

When the nominal storage capacity of this system includes the capacity to recover from "cold soak", the cost of this element is over $600, which is excessive.

The following elements were eliminated from the detailed selection process of the "best" ECS elements for both the electric and hybrid vehicle. The reasons for the elimination are presented.

Hydride (HYCSOS) Heat Pump

This element has a longer term development requirement (beyond the scope of this study).

Jet Compression Heat Pump

This element has a longer term development requirement (beyond the scope of this study). Estimates of the element cost, weight, and volume are not yet available.

Chemical Reaction Energy Storage

This element has a longer term development requirement (beyond the scope of this study).

Intermittent Absorption Energy Storage

The cost of this element is high. The element also has a longer term development requirement (beyond the scope of this study).

Electrically Heated Seats

The effectiveness of electrically heated seats is not clearly defined in terms of ASHRAE comfort criteria (Reference 2-3). It cannot be determined if these elements meet the functional requirements for passenger heating.

Evaporative Cooling

This element does not provide dehumidification. Thus, it does not meet the baseline requirements.

Expendable Refrigerants

The size and weight of this element exceed acceptable limits.

6.0 SELECTION OF THE "BEST" ECS FOR THE ELECTRIC VEHICLE

6.1 SELECTION METHODOLOGY

Selection of the "best" ECS for the electric vehicle is based on the rating scheme developed in Section 2.0. The rating scheme requires that the individual elements be ranked by their rating scores. The formal procedures used to evaluate the elec.ric vehicle ECS elements are summarized in this chapter.

Selection of the "best" ECS for the (near-term) electric vehicle must include evaluation of all factors, including those not directly considered in the numerical rating scheme. For example, of special interest for the emerging electric vehicle technology is the expected market size over the next few years. Evaluation of this factor is dependent on the highly uncertain forecasts of future electric vehicle sales. Hence, it does not lend itself to inclusion in a formal numerical evaluation scheme. This evaluation factor is applied separately to those elements which rank highest in the formal evaluation.

6.1.1 Consideration of Similar ECS Elements

Certain ECS elements had very similar characteristics. In some cases, they belonged to the same group of technologies and used a similar technical approach. To simplify the calculations and presentation of results, the "best" member of the group was chosen to represent that class of technologies, and the remaining members of that subgrouping were not considered further in the evaluat on process.

6.1.2 Ranking of the ECS Elements

Ranking of the electric vehicle ECS elements is as described in Section 3.5. The rating scheme factors and weights are as summarized in Table 3-7.

Actual calculations for each element are carried out on work sheets as shown in Table 6-1. Data sources for these work sheets are the summary tables compiled in Section 4.5 as part of the description of the ECS elements. More detailed data may be found in Reference 1-3.

Table 6-1. Sample ECS Element Worksheet

Electric _____ Hybrid_____ Vehicle

Date ________________ Revisions_____________

1. Name ______ ________________________ ______________

2. Heating _____ (Backup Reqd._____) Cooling ______________

3. Development Status N___________ M_________

4. Data for Rating Scores

Capacity Level →	High	Low
Cost ($)	______	______
Weight (lbs)	______	______
Volume (ft^3)	______	______
Energy Req (Btu/hr.)	______	______
Energy Type	______________	

5. Rating Factor Scores

Capacity Level →	High	Low	Weight
Cost	______	______	0.60
Weight	______	______	0.13
Volume	______	______	0.13
Energy Use	______	______	0.14

6. Total Rating Score	______	______
7. Range Penalty (%)	______	______

8. Comments

Initially, individual data sheets are prepared separately for the heating and cooling elements. Baseline values used to calculate the heating and cooling element rating scores are given in Table 6-2. These values were developed in Section 5.2. Functional forms used to calculate the individual rating factor scores are summarized in Figures 3-2 and 3-3 (from Section 3.2).

The highest ranking heating and cooling elements are combined to produce one or two attractive total ECS elements. These total ECS's are then reranked with the other total ECS elements. The total ECS elements are mainly the reversible heat pumps.

In calculating the characteristics of the total ECS, the weights, the volumes and the costs for the individual ECS elements are summed. Slight savings are potentially available from system integration, but these were not explicitly calculated because they did not appear to make a significant difference in the elements' overall rating score. Energy use is calculated as the average of heating and cooling energy use rates.

6.1.3 Selection of the "Best" ECS

Selection of the "best" ECS for the electric vehicle will be made on the basis of the following three considerations:

- Rating Score Versus Range Penalty Plot
- Status of Technical Development
- Appropriateness for Likely Market Size

Rating Score Versus Range Penalty Plot

A plot of system rating scores versus range penalty is made for all of the total ECS elements. This plot quickly shows which ECS elements are the more desirable in terms of the rating scheme. It also explicitly satisfies the JPL requirement to indicate the elements ranking independently of the range penalty (Reference 1-5).

Status of Technical Development

Table 3-4 establishes the definitions for the state of development used in this study from Section 3.2. The evaluation will treat only near and mid-term ECS elements. As suggested by JPL (Reference 1-5), only a

Table 6-2. Baseline Values for Calculation of ECS Element Rating Scores - Electric Vehicle

Element Type		Heating	Cooling	Total
Rating Parameter				
Cost	($)	85	470	555
Weight	(kg)	9	45	54
	(lb)	20	100	120
Volume	(m^3)	0.042	0.13	0.17
	(ft^3)	1.5	4.5	6.0
Energy Use	(watt)	2,855*	6,858**	4,856
	(Btu/hr)	9,740	23,400	16,570

*Based on combustion heater and used solely for comparative ECS evaluation.

**Based on Otto (Gasoline Engine) vapor compression cooling and used solely for comparative ECS evaluation.

near-term ECS can be recommended for immediate development. A mid-term ECS would be recommended for more extensive development only if it appeared to be very attractive compared to the near-term system. Long-term systems are considered "out of scope" for this study.

Appropriateness for Market Size

As discussed in Section 3.4, achieving low cost in the automotive industry is based on achieving large scale production levels at minimum risk. Alternately, for limited production vehicles, a high percentage of components are purchased at favorable prices from existing manufacturers already in high volume production for other purposes.

Figure 6-1 summarizes the production levels that can be expected for electric vehicles in the near-term. Only with very optimistic forecasts of increased electric vehicle production can electric vehicles be assumed to be "mass produced" in the next few years. Hence, there is a strong incentive to select ECS elements from technologies already produced in large quantities.

6.2 EVALUATION OF CANDIDATE SYSTEMS

6.2.1 Elements Not Considered in the Electric Vehicle Evaluation

The following ECS element was not considered further in the electric vehicle evaluation:

- Eutectic TES Cooling - In general, ice making TES cooling had almost identical or slightly more favorable properties in comparison to eutectic TES cooling. Eutectic TES cooling was not considered further because they were essentially similar systems.

6.2.2 Ranking of Heating and Cooling Elements

Since only one heating element (the combustion heater) remained under consideration, no ranking was performed for the heating elements. Ranking for the cooling elements is shown in Table 6-3. Because there was not a strong difference between rating scores on these three elements, all three are carried forward into the final evaluation. The results are three total ECS's combining the combustion heater with each of the cooling elements (Otto vapor compression, Otto ROVAC, and Ice Making).

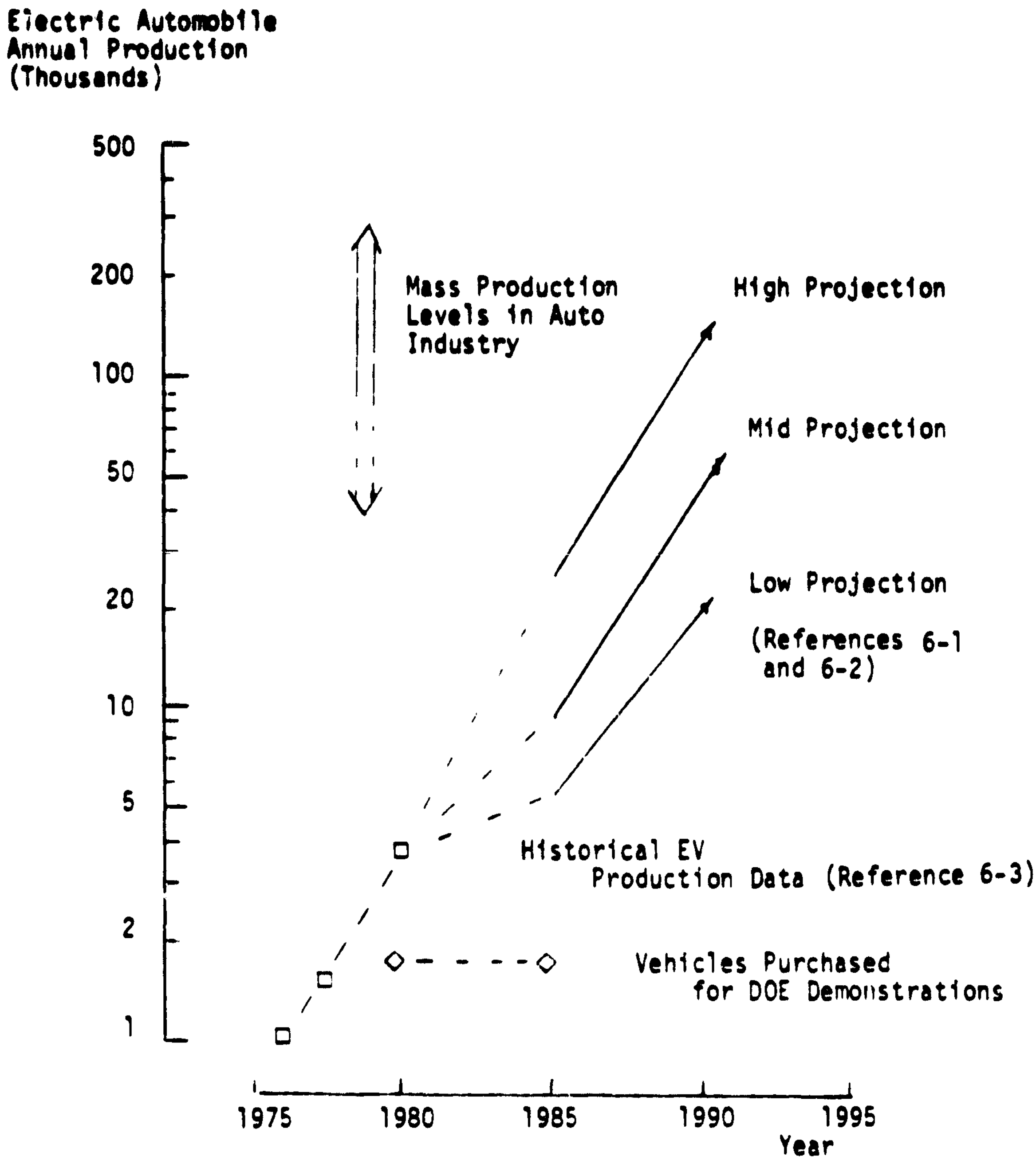


Figure 6-1. Projections of Electric Automobile Production for the United States

Table 6-3. Ranking of the Cooling ECS Elements for the Electric Vehicle

Element	Rank	Rating Scores	Range Penalty
Otto ROVAC Cooling	1	63-72	2-4%
Ice Making Cooling	2	55-64	8-10%
Otto Vapor Compression Cooling	3	47-59	3-5%

*Derived from data in Section 4.0 using format of Table 6-1.

6.2.3 Rating Score versus Range Penalty

The number of elements in the final evaluation is small. Thus, all were considered in the final evaluation of rating score versus range penalty, as shown in Figure 6-2. It should be noted that this plot contains systems in alternate states of development and not directly comparable. Only the near term systems are candidates for the "best" ECS. Rating scores are given for two levels of capacity. This gives some indication of the variation in the rating scores possible for each element. It also indicates that only differences in the rating scores of 20 points or greater can be regarded as significant.

6.2.4 Choice of "Best" ECS

The Combustion Heater and Otto Vapor Compression Cooling System appears to be the "best" ECS for the electric vehicle. See Table 6-4. Technically, all of the systems are quite similar with the combustion heater and Otto ROVAC cooling having a slight edge in the rating scheme. However, only the vapor compression system is proven in widespread automotive use. When combined with a small Otto (gasoline) engine drive, the combination has good technical characteristics and is very appropriate for limited scale production. The combustion heater, the vapor compression air conditioner components, and the Otto (gasoline) engine drive are all available in large quantities from existing production facilities.

Mid-Term Development

Potentially, other technical systems could offer additional advantages to future electric vehicle designs. Based on the data available to this study on existing systems being developed for mid-term applications, the Ericsson Ericsson heat pump appears attractive.

However, development in battery technology, such as the higher energy density batteries (Reference 3-8) could change the choice of advanced technology. For example, if a high energy density battery is used the current range penalty could be relaxed. This might favor consideration of an Electric Ericsson heat pump, in lieu of the gasoline burning Ericsson Ericsson cycle. The rating score of the Electric Ericsson heat pump is quite high and if the 20% range penalty limit is relaxed, it is a very favorable system. See Figure 6-3.

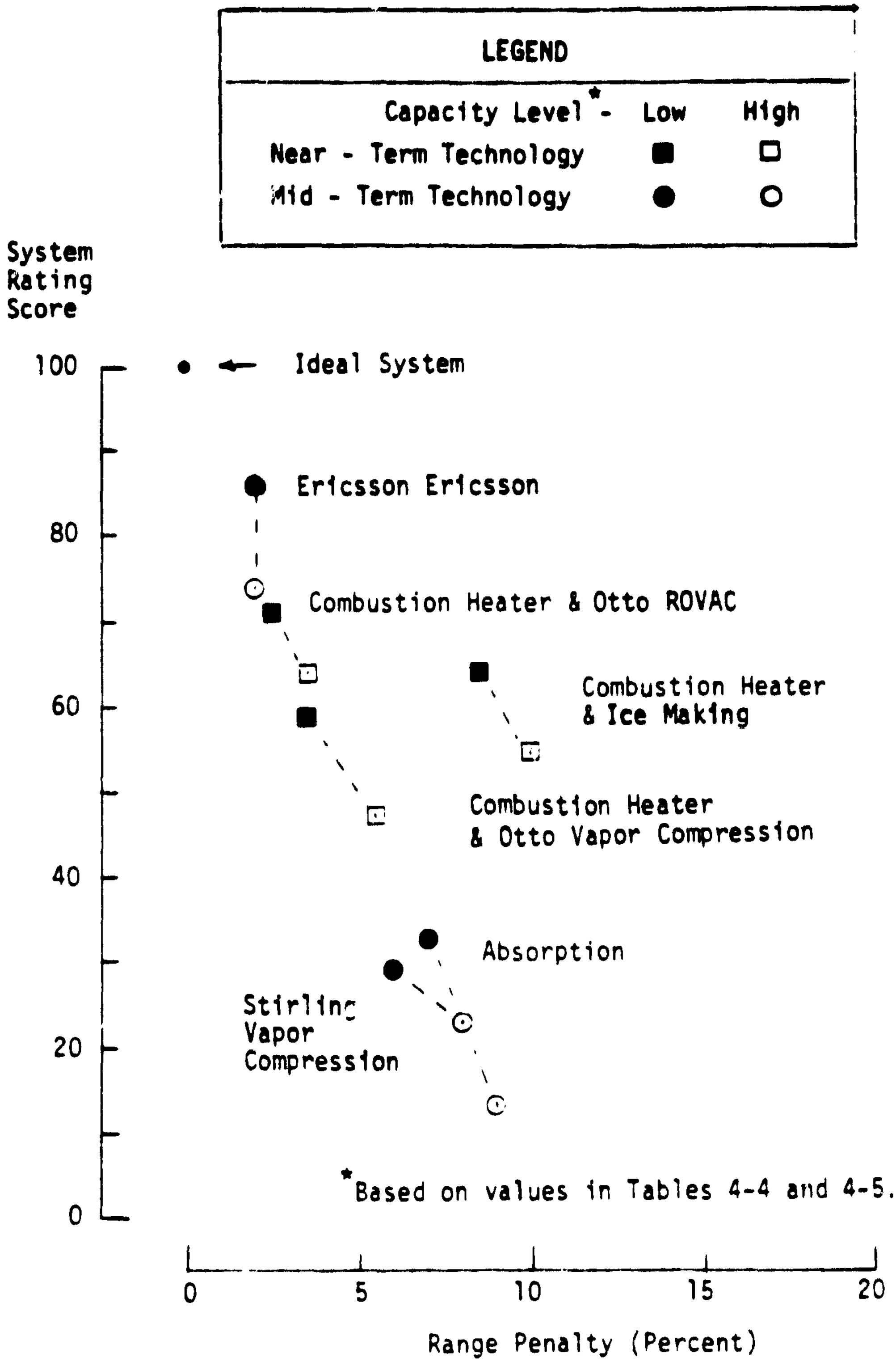


Figure 6-2 Rating Score versus Range Penalty for Electric Vehicle ECS Alternatives

Table 6-4. Summary of Factors for Selection of "Best" ECS for Electric Vehicle

Technology	Technical Characteristics	Appropriateness for Likely Market Size - i.e., Limited Production
Otto ROVAC Cooling	Highest Rank - But not significantly superior	Requires limited production of special ROVAC components for automotive application.
Ice Making Cooling	Second Rank - Significantly higher range penalty	Requires limited production of special TES components for automotive application. Components not demonstrated in automotive service.
Otto Vapor Compression Cooling	Third Rank - But not significantly inferior	Can be built completely from components already available for automotive service.

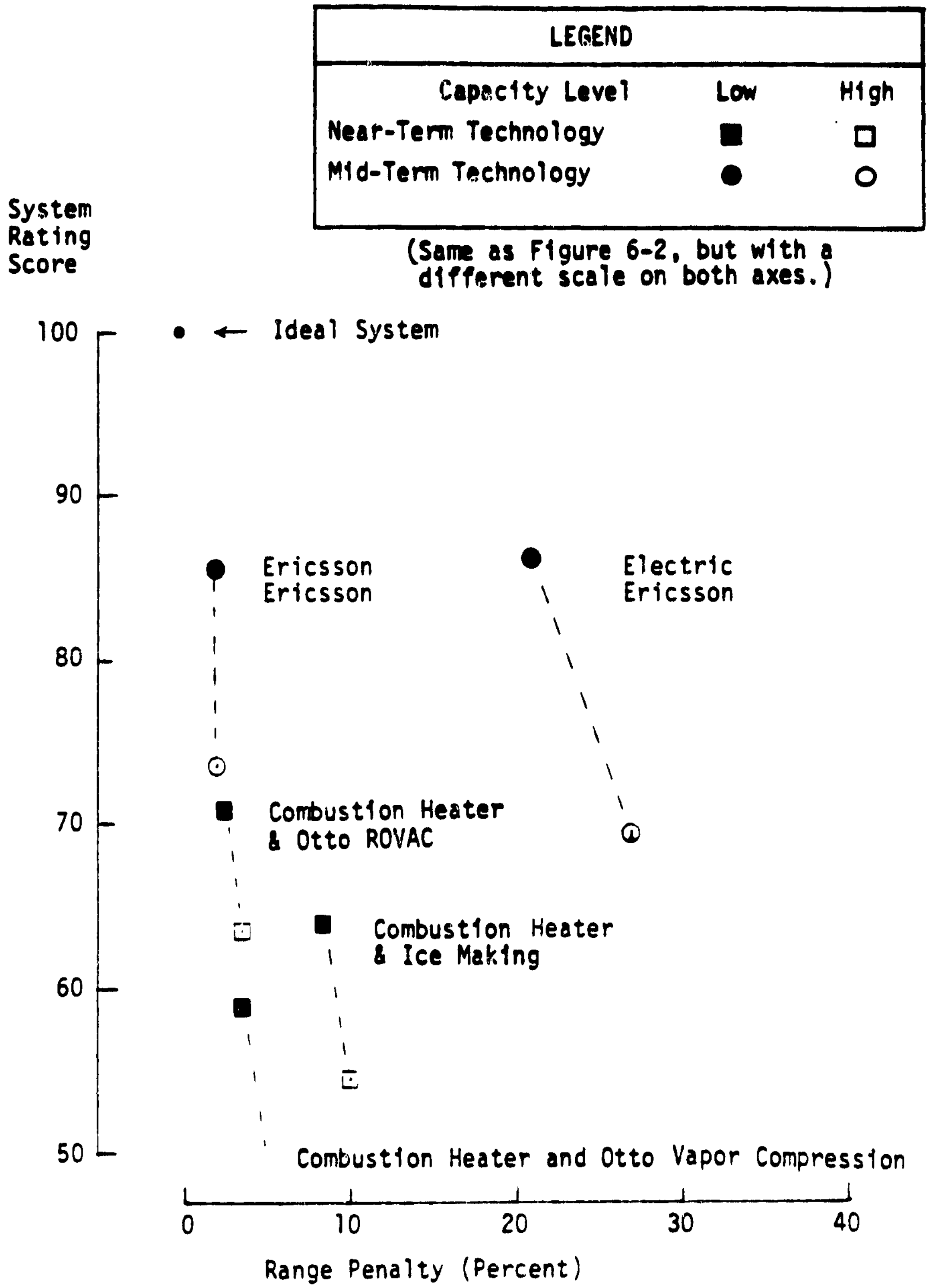


Figure 6-3 Relative Evaluation of Electric Ericsson with Range Penalty Limit Above 20%

Even with a near term nickel-iron or nickel-zinc battery, the occasionally occurring range penalty of about 25% might be acceptable to vehicle users. Hence, the recommended strategy for more advanced development is to conduct parallel development of both gasoline (fossil fuel fired) and electrically driven advanced heat pumps with favorable characteristics, such as the Ericsson cycle.

6.3 COMMENTS ON EVALUATION

Selection of the Combustion Heater and Otto vapor compression cooling as the "best" ECS reflects the experience already acquired by electric vehicle developers.

Both the General Electric and Garrett Near Term Electric Vehicles use combustion heaters (Reference 5-3). This is also typical of most commercially produced electric vehicles. Hence, the use of the combustion heater is supported as a pragmatic choice of vehicle designers.

Selection of the Otto vapor compression cooling element is also a matter of pragmatic choice because it minimizes development risk. As discussed in Section 3.4, the automotive industry tends to be "conservative". For a limited production market, the Otto vapor compression cooling system minimizes risk because it requires the smallest amount of capital investment by the vehicle manufacturer until his market is established. The small and uncertain future market for the electric vehicle ECS justifies the conservative choice of technology.

Even the best technology evaluated in this study, the Ericsson Ericsson heat pump, offers advantages not readily perceived by the market. The average owner will not realize that the Ericsson Ericsson ECS is much smaller and more efficient than Otto vapor compression ECS. He only sees that the price is the same. Hence, unless the cost of operating the ECS becomes a key issue, there is little perceived advantage in the advanced options.

Gasoline Engine Life

The only other uncertainty in this evaluation is the lifetime of the small gasoline engine in the ECS. Service life of small gasoline engines is highly dependent on design and construction practices. Small, fast turning engines tend to have much shorter operating lives than larger, slow turning engines. The data base given in the report is for industrial engines with service lives of "several hundred hours." (Reference 6-4) However, care in selecting the engine drive for the ECS would be required to ensure adequate lifetime for automotive service.

In general, engine life can be extended by the following:

- Careful design of the valve train
- Operating at low engine speeds
- Using hardened and plated pistons and rings
- Assuring good lubrication and cooling (See Reference 6-5 for details.)

Conservative design practice would dictate that the ECS have a design life of 3,000 to 5,000 hours.

7.0 BATTERY HEATING AND COOLING ECS

The battery heating and cooling ECS has been treated separately from the main ECS discussed in Section 6.0. This is because the additional loads caused by the battery ECS are small compared to the "main" ECS loads. Battery ECS load can be handled within the design range of the main ECS loads.

The current design for the battery ECS is based on the (revised) JPL Guidelines (Reference 2-9). This requires the battery pack to be maintained at 49°C ± 6°C (120°F ± 10°F). The ECS design is based on this requirement, assuming the battery pack is insulated with 2.54 cm (1.0 in) of mineral fiber insulation.

7.1 BATTERY HEATING AND COOLING

7.1.1 Heating

The energy required to maintain the battery at its operating temperature of 49°C (120°F) at -29°C (-20°F) ambient is about 380 watts (1300 Btu/hr). This could be provided by a small electric maintenance heater, but would result in battery self discharge in about 2 days. A more practical approach is to provide a means of diverting the combustion heater output to the battery compartment. When the vehicle is idle, operation of the heater for a few minutes out of every hour could provide the required level. During vehicle operation, the required supplemental heat represents less than 10% additional capacity for the heating system ECS. A fairly simple control system would allow the combustion heater to meet both the passenger compartment and battery compartment heating requirements.

7.1.2 Cooling

Battery cooling would be accomplished by blowing ambient air through an annular region around the battery pack. This flow pattern is illustrated in Figure 7-1. If a 1.25 cm (0.5 in) air space is available all around the battery, the annular flow area is 132 cm^2 (20.4 in^2). With a cooling air flow of 119 m^3/hr (70 cfm), as derived in Table 2-10, the air flow velocity is approximately 2.6 m/sec (8 ft/sec).

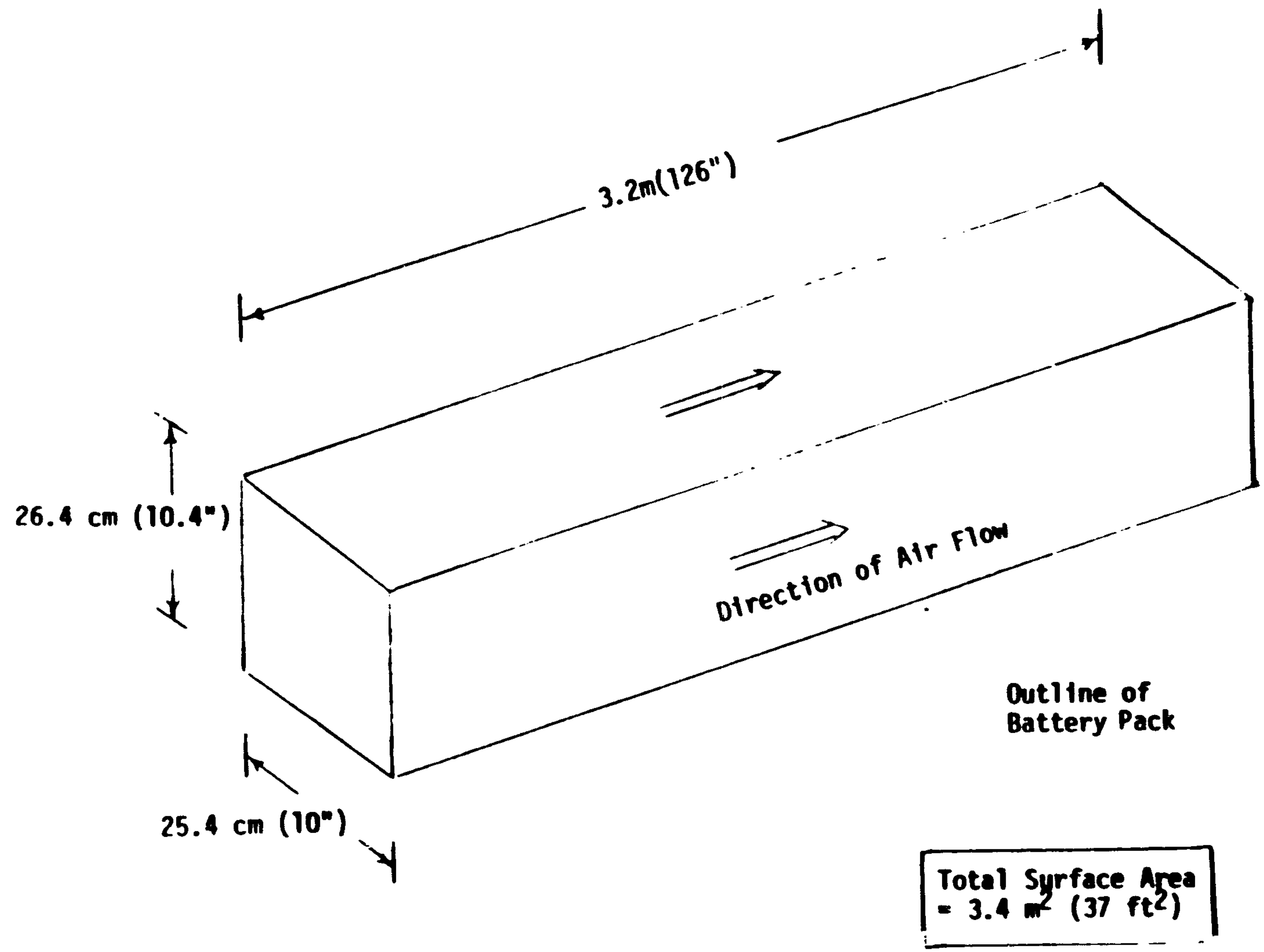


Figure 7-1. Illustration of Battery Cooling Air Flow

Assuming the battery surface is rough, the surface heat transfer coefficient would be about 12.6 watt/m^2 (4 Btu/ft^2-hr). (See Figure 7-2). If the batteries maximum heat evolution rate is 225 watts (767 Btu/hr) during an 8 hour charge, than the required temperature differential between the battery pack and the ambient air is 3°C (5.4°F). If the surface of the battery pack is at 54°C (130°F) average, then cooling with ambient air at 49°C (120°F) is adequate.

7.2 SUMMARY OF BATTERY ECS

The battery ECS consists of the following:

- Provision for diverting part of the combustion heater output to the battery pack compartment under normal operating conditions. This includes adding approximately 10% to the design range heater capacity to cover the additional load.

- Provision for diverting the combustion heater's full output to the battery compartment for providing maintenance heating when the vehicle is idle.

- A separate blower for circulating ambient cooling air and providing positive ventilation of the battery compartment. (The required power level is about 100 watts.)

The operation of these components would be appropriately controlled by the battery temperature controller.

ECS for Lower Battery Temperatures

If lower battery temperatures were desired, then battery cooling could be implemented using the cooling ECS element. When the vehicle is in operation, the exhaust air from the passenger compartment might be adequate to cool the battery. In any event, the additional cooling load would be less than 10% of the capacity for passenger compartment cooling. Furthermore, if ambient temperatures are low enough, i.e., five degrees (centigrade) less than the desired battery temperature, ambient air can be used for battery cooling. Thus, changing the battery ECS temperature requirement will not significantly affect the overall ECS design.

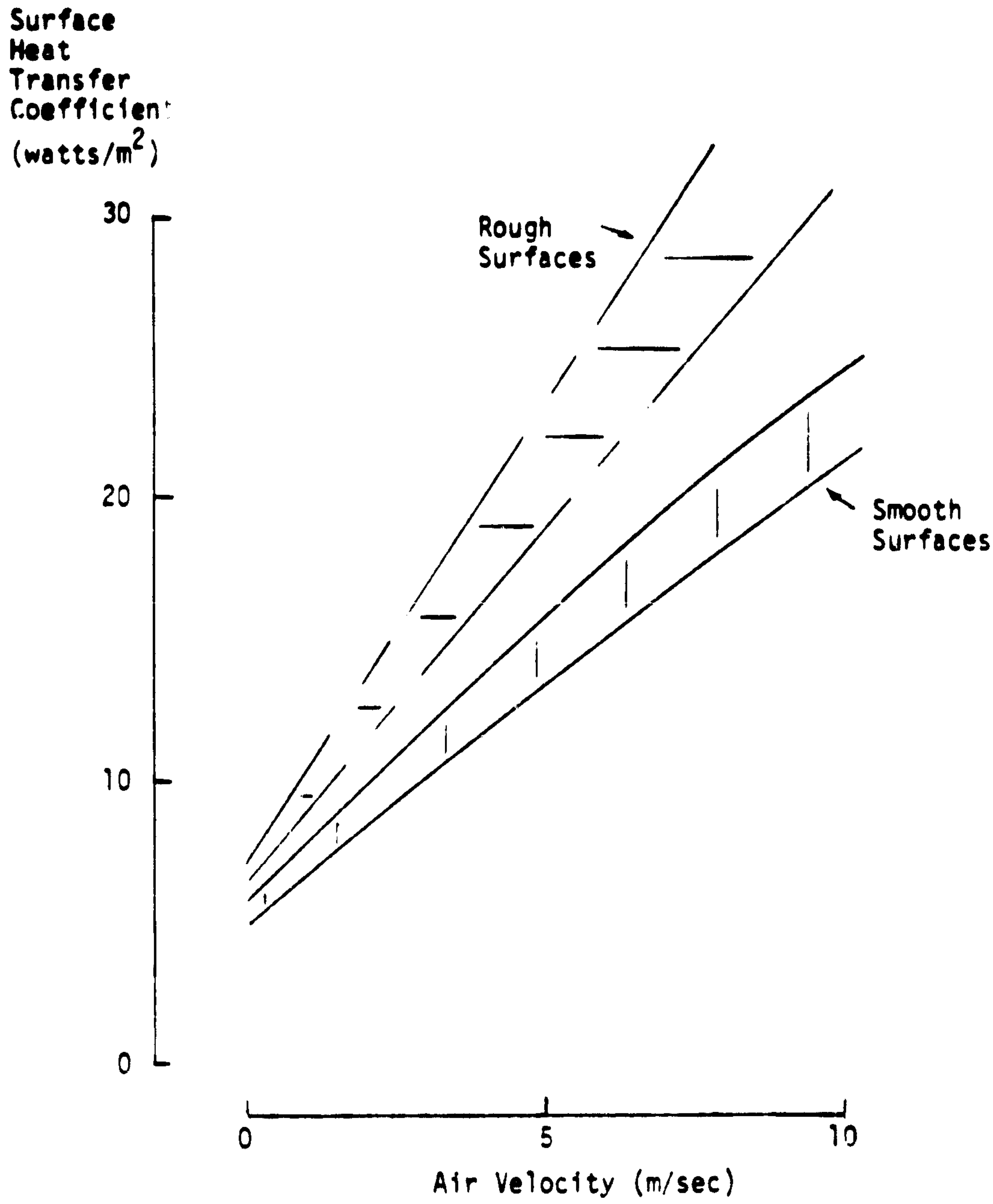


Figure 7-2. Surface Heat Transfer Coefficient as a Function of Air Velocity

8.0 SELECTION OF THE "BEST" ECS FOR THE HYBRID VEHICLE

8.1 EXPECTED CHARACTERISTICS FOR THE HYBRID VEHICLE

Selection of the "best" ECS for hybrid vehicle requires a clear definition of the hybrid vehicle. Recently, results of studies by DOE/JPL contractors (Reference 8-1 and 8-2) have provided fairly complete definitions of hybrid vehicles. These definitions are used as the basis for selecting the "best" ECS for the hybrid vehicle.

8.1.1 JPL Requirements

JPL defined the hybrid vehicle in terms of its range and passenger carrying characteristics. (See Table 8-1.) The JPL concept of the hybrid vehicle included a large battery pack and a small heat engine. This maximized use of utility generated electricity and minimized use of petroleum fuel. Because the heat engine is small, use of mechanical power from the engine would be undesirable and might severely impact the vehicle's capacity to accelerate.

8.1.2 Vehicle Characteristics from the DOE Phase I Program

During Phase I of the DOE Near Term Hybrid Vehicle Program, four contractors executed independent hybrid vehicle designs. The range of the key parameters for these vehicles is summarized in Table 8-2. These vehicle designs generally meet the JPL requirements for vehicle passenger capacity and operating range. However, in general, they have much larger heat engines, so considerably more mechanical power is available to drive accessory loads. In fact, design data presented in the current Phase II design (Reference 8-2) shows a mechanical power take off provided for the accessories, such as the air conditioner and power steering pump. With a combined heat engine and electric motor power level of nearly 74.6 kW (100 HP) available, the requirement of a few kW for the air conditioner should be within the power system's capacity under most vehicle operating conditions.

It should also be noted from Table 8-2 that the lead acid battery pack is approximately two thirds the capacity of the battery pack in the electric car. This potentially reduces the loads for the battery ECS.

Table 8-1. Key JPL Requirements for Hybrid Vehicle Characteristics

1. Designed for 5 passengers and extended range operation (Approximately 400 km (250 miles) between fueling stops).

2. The battery pack is (assumed to be) identical to the electric vehicle.

3. Initial charging of the batteries is from utility power. Charging during operation will be from intermittent operation of a heat engine and generator (Heat engine power approximately 18.6 kW (25 HP)).

4. (Mechanical) power from the engine will not be available to drive the ECS.

5. Fuel allocation to the ECS will not exceed 19 liters (5 gallons).

Source: Reference 1-5

Table 8-2. Range of Key Vehicle Parameters from DOE Phase I - Near-Term Hybrid Vehicle Program

Design Parameter	Range of Values	For Current Design
Passenger Capacity	5 to 6	5
Maximum Range		
Urban (km)	167 to 385	167*
Urban (mi)	104 to 239	104*
Highway (km)	270 to 499	399
Highway (mi)	168 to 310	248
Heat Engine Power (kW)	36.2 to 52.2	44.7
(HP)	48.5 to 70	60
Heat Engine Power Fraction	0.51 to 0.67	.59
Battery Capacity (kWh)	12.5 to 17.5**	12.5

*Range at which heat engine operates continuously.

**Actual battery capacity range for lead acid batteries was 12.5 to 12.6 kWh.

Source: References 8-1 and 8-2

8.1.3 Range Penalty for Hybrid Vehicle

The ECS system can reduce the range of the hybrid vehicle in several ways. These include:

- Reducing the amount of gasoline available for the heat engine
- Increased vehicle weight
- Increased vehicle aerodynamic drag cross section.

This listing presumes that any energy drawn from the battery (as electricity) will be replaced by consuming gasoline in the heat engine to recharge the battery.

In the electric vehicle evaluation, it was found that only the range penalty based on electric (propulsion battery) energy use had a significant impact. Hence, only energy use was considered in calculating the range penalties for the hybrid vehicle ECS.

The range penalty for energy use can be constructed from the predicted characteristics of the hybrid vehicle as shown in Table 8-3. In this case, the percentage range penalty for each gallon of gasoline used by the ECS can be calculated in terms of the vehicle's marginal fuel economy. The same approach can be used for electrical energy consumed, except that this must be divided by the efficiencies of the engine and generator respectively. (Again, this assumes the engine generator replaces any electrical energy consumed from the battery pack.)

When the heat engine begins to operate, large amounts of waste heat (over 30 kW or 100,000 Btu/hr) will be available. Hence, the heating ECS needs only to operate for a limited period of time. By contrast, the cooling ECS needs to operate for the entire period of vehicle operation. While the figure given in Table 8-3 is arbitrary, this value was used consistently in all evaluations. Actual vehicle operation between refueling could be for longer periods, with higher range penalties involved.

8.1.4 Discussion of Hybrid Vehicle Influence on ECS Design

The hybrid vehicle potentially offers considerably more flexibility in the choice of an ECS because more total energy is available from the gasoline

Table 8-3. Calculation of Range Penalty for Hybrid Vehicle (Based on Selected Phase I Design)

1. Vehicle Characteristics -

Maximum Range	-	399 km (248 mi)
Marginal Fuel Economy*	-	14.5 km/l (34 MPG)
Assumed Average Speed**	-	39.8 kph (24.7 MPH)
First Heat Engine Operation	-	120 km (74.5 mi)

2. Powerplant Characteristics -

Heat Engine Efficiency	- 0.25 (Max)
Generator Efficiency with Control	- 0.85

3. Range Penalty Per Gallon of Gasoline Used

Range Penalty = Marginal Fuel Economy/Maximum Range = 12%/Gallon

4. Range Penalty Per kWh of Electricity Used =

Gallons of Gasoline to Generate One kWh x Gasoline Range Penalty

3412 Btu/(.85 x .25) = 16,055 Btu = 0.128 Gallon of Gasoline

Range Penalty = 1.54%

5. Operating Time Until First Heat Engine Operation

Operating Time = 3 hours

6. Assumed Operating Time Between Refuelings

Operating Time = 6 hours

Note: Vehicle is capable of operating up to 10 hours between refuelings

Source: References 8-2 and 8-6

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*Fuel economy after battery energy is exhausted.

**Mix of 65% urban and 35% highway driving.

tank. However, more energy will be needed because of the potentially longer operating periods. Hence, the emphasis in selecting the "best" ECS will be placed on efficient systems which minimize the use of gasoline energy.

Data from the Phase I Near Term Hybrid Vehicle studies indicate that direct mechanical drive for the ECS is feasible. Since the total power (neat engine plus electric motor) in the hybrid vehicle approaches 74.6 kW (100 HP), taking a few kW for the ECS should not penalize vehicle acceleration. If this is a potential problem, the mechanically driven ECS can be "declutched" during occasional requirements for peak power system output without noticeable loss in function. Similar systems have already been proposed for vehicles with small heat engines (Reference 8-3).

The biggest change in the power system will be the requirement to supply auxiliary shaft power when the vehicle is stationary. This can be done by the propulsion motor with controls to allow for efficient part load operation.

8.2 SELECTION METHODOLOGY

Selection of the "best" ECS for the Hybrid Vehicle is based on the rating scheme developed in Section 2.0. The rating scheme requires that the individual elements be ranked by their rating scores. However, stringent application of the functional requirements to certain systems resulted in their being found inappropriate for use in hybrid vehicles in Section 5.0.

Selection of the "best" ECS for the (near-term) hybrid vehicle must include evaluation of all factors, including those not directly considered in the numerical rating scheme. Of special interest for the hybrid vehicle is the expected size of the emerging market for these vehicles over the next few years.

8.2.1 Elimination of Additional ECS Elements from the Hybrid Vehicle Evaluation

Additional ECS elements were eliminated from consideration for the hybrid vehicle for two reasons. First, the very long potential mission time requirement for the hybrid vehicle effectively limited the ECS elements to those operating from onboard gasoline or electrical energy.

Second, as discussed in Section 6.1.1, certain ECS elements had very similar characteristics. In some cases, they belonged to the same group of technologies and used a similar technical approach.

To simplify the calculations and presentation of results, the "best" member of the family was chosen to represent that class of technologies, and the remaining members of that subgrouping were not considered further in the evaluation process.

8.2.2 Ranking of the ECS Elements

Ranking of the hybrid vehicle ECS elements is as described in Section 3.5 and parallels the discussion in Section 6.1.2. The rating scheme factors and weights are as described in Table 3-7.

Actual calculations for each element are carried out on work sheets as previously shown in Table 6-1. Data sources for these work sheets are the summary tables compiled in Section 4.5.

As for the electric vehicle, individual data sheets are prepared separately for the heating and cooling elements. Baseline values used in calculation of the heating and cooling element rating scores are given in Table 6-2. (These values were developed in Section 5.2). The only difference is that energy use is calculated on the basis of the total energy (in gasoline equivalent Btu) used by the ECS for the entire mission. The baseline energy use values for the hybrid ECS are given in Table 8-4. As described previously, the combined ECS energy use value is the average of the heating and cooling values.

Functional forms used in calculating the individual rating factor scores are the same forms used for the electric vehicle ECS evaluation and are summarized in Figures 3-2 and 3-3 (from Section 3.2).

The highest ranking heating and cooling elements are combined to produce one or two attractive total ECS elements. These total ECS's are then reranked with the other total ECS elements. The total ECS elements are mainly the reversible heat pump cycles.

In calculating the characteristics of the total ECS, the weights, the volumes, and the costs for the individual ECS elements are summed. Slight savings are potentially available from system integration, but these were

Table 8-4. Baseline Energy Use Values for Hybrid Vehicle ECS*

Heating ECS

Baseline energy rate (for combustion heater)	=	2.85 kW (9,740 Btu/hr)
Maximum Operating Time	=	3 hr
Baseline Heating Energy	=	8.55 kWh (29,220 Btu)

Cooling ECS

Baseline Energy Rate (for Gasoline Rankine cooling)	=	6.86 kW (23,400 Btu/hr)
Maximum Operating Time	=	6 hr
Baseline Cooling Energy	=	41.1 kWh (140,400 Btu)

Total ECS

Average Baseline ECS Energy	=	24.9 kWh (84,810 Btu)

*Baseline energy use values are solely for purposes of comparative ECS evaluation.

not explicitly calculated because they did not appear to make a significant difference in the elements' overall rating score.

8.2.3 Selection of the "Best" ECS for the Hybrid Vehicle

Selection of the "best" ECS for the hybrid vehicle was done on the basis of three considerations. These were:

- Rating Score versus Range Penalty Plot
- Status of Technical Development
- Appropriateness for Likely Market Size

Rating Score Versus Range Penalty Plot

A plot of system rating scores vs. range penalty was made for all of the total ECS elements. This plot quickly shows which ECS elements are the more desirable in terms of the rating scheme.

Status of Technical Development

Table 3-4 establishes the definitions for the state of development used in this study from Section 3.3. The evaluation treats the first two cases separately. Only a near-term ECS can be recommended for immediate development for the hybrid vehicle.

Appropriateness for Market Size

Hybrid vehicle production is likely to be even lower than the projections given for electric vehicles in Figure 6-3. Currently, there is no regular production of hybrid vehicles. The total number of prototype hybrid vehicles in existence is about 100. Development of near term hybrid vehicle prototypes by the Department of Energy lags comparable electric vehicle development. A recent DOE paper (Reference 8-4) forecasted hybrid vehicle "commercialization" as happening at least two years after electric vehicle "commercialization". At best, hybrid vehicle production is expected to be about half of EV production for the near future.

Thus, hybrid vehicles can be expected to be in limited production throughout the near term period. This provides a strong incentive to choose hybrid vehicle ECS elements from technologies which are already produced in large quantities for other applications.

8.3 EVALUATION OF CANDIDATE SYSTEMS

8.3.1 Discussion of Elements Eliminated for the Hybrid Vehicle Evaluation

All energy storage elements were eliminated from the hybrid vehicle evaluation. This was done because the operating period of up to ten hours for the hybrid vehicle required storage systems of excessive size and cost. Thus, for the hybrid vehicle, any form of energy storage rapidly becomes impractical, except for fossil fuel.

8.3.2 Ranking of Heating and Cooling Elements

With the elimination of the energy storage elements from consideration, only two heating and four cooling elements remained in the evaluation. Rankings for the heating and cooling elements, shown in Table 8-5, were actually considered to be quite close, especially when the differences in range penalty were considered.

Hence, it seemed appropriate to consider combinations of these systems that were logical. The combustion heater was combined with the Otto ROVAC and vapor compression cooling elements. The electric resistance heater was paired with the electric ROVAC and vapor compression cooling elements. The electric ROVAC system was not considered in the final analysis because of its large range penalty when combined with the resistance heater.

8.3.3 Rating Score versus Range Penalty

Since the number of elements in the final evaluation was small, all elements were considered in the final evaluation of rating score versus range penalty, shown in Figure 8-1. It should be noted that this plot contains systems in alternate states of development and not directly comparable. Only the near term systems are candidates for the "best" ECS. Rating scores are given for two levels of capacity. This gives some indication of the variation in the rating scores possible for each element. It also indicates that only differences of 20 points or greater in the rating scores can be regarded as significant.

Table 8-5. Ranking of Heating and Cooling ECS Elements for the Hybrid Vehicle

Element	Rank	Rating Scores*	Range Penalty (%)
Heating			
Resistance Heater	1	72-74	11-14
Combustion Heater	2	15-40	3-4
Cooling			
Otto ROVAC	1	68-75	20-26
Electric ROVAC	2	54-62	23-29
Otto Vapor Compression	3	32-57	13-17
Electric Vapor Compression	4	30-50	15-19

*Derived from data in Section 4.0 using format of Table 6-1.

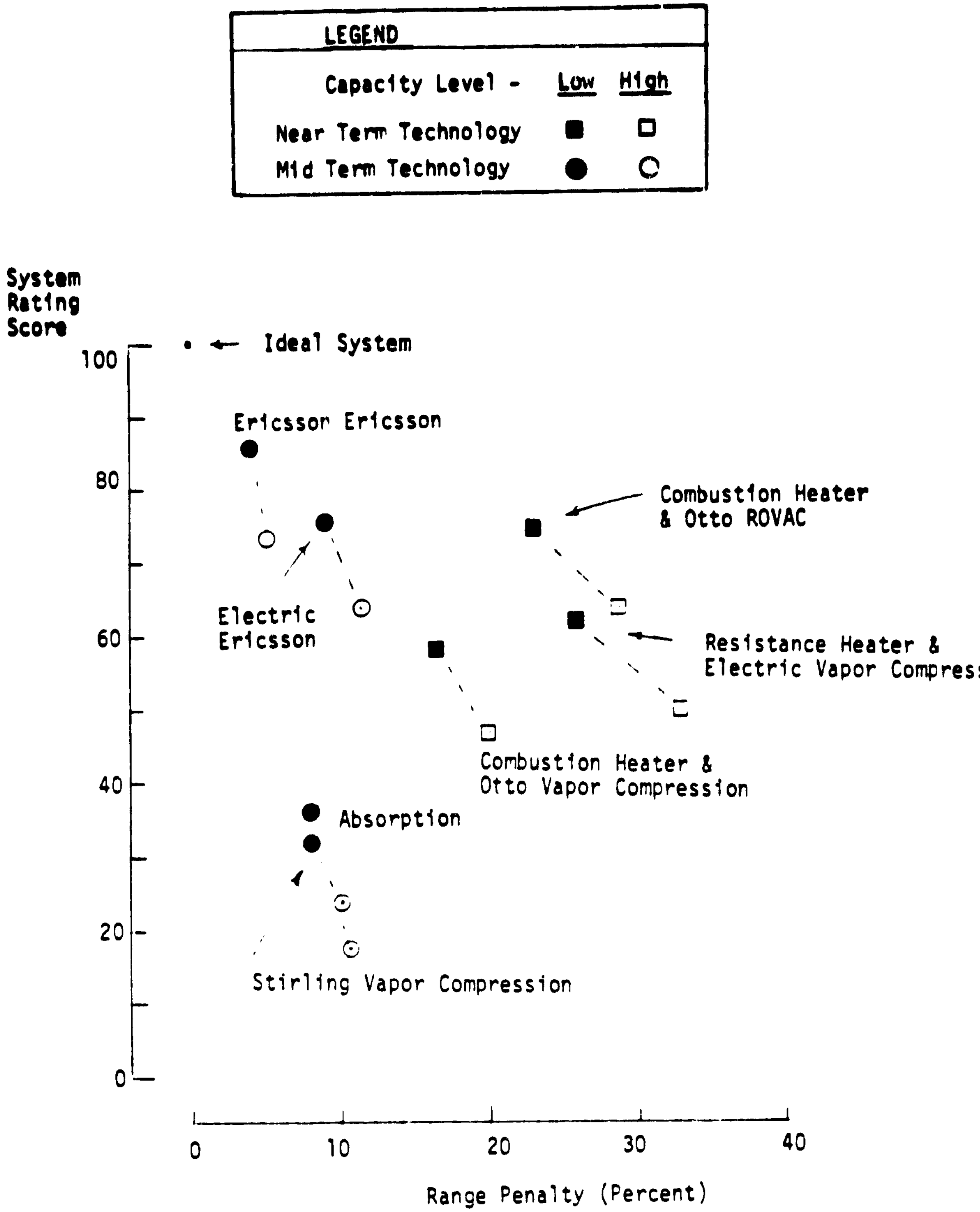

Figure 8-1. Rating Score vs. Range Penalty for Hybrid Vehicle ECS Alternatives

Note on Absorption System

The absorption system potentially could be driven by engine waste heat when it comes available. The evaluation of the absorption system is based on this favorable premise. Direct fuel consumption is assumed to be required for only the first 3 hours of operation. After this 3 hour period, the system is assumed to be driven by waste heat. However, because of its large size and weight, as well as its high cost, the absorption system still tends to rate low in the overall evaluation.

8.3.4 Choice of "Best" ECS

The choice of "best" ECS for the hybrid vehicle is less straight forward than for the electric vehicle. Clearly, the combustion heater is the more desirable choice for the heating ECS element because it avoids the large range penalty associated with the electric resistance heater. The choice of cooling systems is harder, because the rating scores of the systems are very close. The Otto (gasoline engine) vapor compression and electric vapor compression systems appear to be "best" because they utilize hardware which is already in widespread automotive use. The key question is how to drive the vapor compression cycle.

If use of a mechanical drive from the main engine motor system is permitted, this will probably be the preferred method. Alternately, an electrically driven vapor compression system is the most reliable.

In all cases, the preferred systems, i.e., the combustion heater and the electrically or mechanically driven vapor compression cycle are available in large quantities from existing production facilities. Hence, they are appropriate for the expected "limited production" size of the hybrid vehicle market.

Mid-Term Development

Potentially, other technical systems could offer additional advantages to future hybrid vehicle designs. Based on the data available to this study on existing systems being developed for mid-term applications, the Ericsson Ericsson and Electric Ericsson heat pumps appear attractive.

As with the electric vehicle, the recommended strategy for more advanced development is to conduct parallel development of both gasoline (fossil fuel fired) and electrically driven advanced heat pumps.

8.4 COMMENTS ON EVALUATION

There is less experience with hybrid vehicles which can be used to justify the choice of "best" ECS. Table 8-6 summarizes the limited experience from the Near-Term Hybrid Vehicle Program.

Selection of the combustion heater and vapor compression cooling element is also a matter of pragmatic choice because it minimizes development risk. As discussed in Section 3.4, the automotive industry tends to be "conservative". For a limited production market, this particular ECS minimizes risk because it requires the smallest amount of capital investment by the vehicle manufacturer until his market is established. The very small and uncertain future market for the hybrid vehicle ECS justifies the conservative choice of technology.

The fact that the advanced ECS technologies offer performance, but not price advantages, tends to reinforce this choice. The consumer is mainly aware of price differences, but not aware of subtle differences in system performance.

Table 8-6. Choices of Heating and Cooling ECS Elements From Near-Term Hybrid Vehicle Program (Phase I)

Contractor	Heating/Cooling ECS	Reference
General Electric	Combustion Heater with Engine Waste Heat Recovery/Provision for Mechanical Drive of vapor compression cooling ECS from engine	8-3
Minicars	Combustion Heater/Engine Driven vapor compression cooling ECS	8-5

Note: Summary Reports by the other contractors contained no data on proposed ECS design.

9.0 PROPOSED PROGRAM FOR ECS PROTOTYPE DEVELOPMENT

9.1 DISCUSSION OF DEVELOPMENT APPROACH

In order to formulate a realistic development program, the following three important aspects of the development process must be considered:

- Component Selection
- System Integration
- Test Procedures

How these factors affect specific portions of the development program is discussed in the following sections.

9.1.1 Component Selection

Since the selected ECS design is largely built from existing components, component selection is critical to having a successful design. For several of the key components this is not a serious problem, since they are already in widespread automotive service. However, for some components it may be hard to get critical data on their lifetime and their ability to function reliably in the automotive environment. Careful screening, selection, and testing of these components may be necessary to ensure that the system meets all functional and acceptability criteria.

9.1.2 System Integration

All of the ECS components must work well together and work well with the existing vehicle characteristics. An integrated design that achieves good performance from all components is necessary. A control system must be provided to properly integrate the components into a system. The system must be capable of operating in an efficient fashion to meet several functional requirements at the same time. The control system also must sense and prevent inappropriate or potentially harmful operation of the system components under various possible control inputs from the vehicle operator or from unusual operating conditions.

Complete and successful system integration will require analysis and evaluation of the system under a wide variety of possible operating conditions to ensure safe and proper functioning of all system components.

9.1.3 Realistic Test Procedures

Because of the complex nature of the automobile and automotive systems, extensive testing is important to ensure satisfactory system operation. At a minimum, three broad categories of testing are required to ensure its satisfactory performance of the final ECS design in actual service. These categories are:

- Operational Testing
- Acceptability Testing
- Reliability Testing

Operational Testing

The ECS would need to be tested in the operating vehicle under the rated ambient conditions to ensure the ECS could meet all of the functional requirements. The vehicle can be subjected to the extreme ambient conditions in special test facilities as indicated in Table 9-1. Climatic wind tunnels represent a more controlled environment for vehicle testing, with the ability to place extensive instrumentation in the vehicle. Field test facilities, however, can also provide an adequate basis for subjecting a vehicle to extreme temperature conditions.

Special test facilities (cold rooms) for conducting the Federal Motor Vehicle Safety Standard Test 103 are also available in the automotive industry.

Acceptability Testing

Aside from fulfilling the operational requirements, the ECS must be acceptable to the vehicle user in terms of:

- Noise Levels
- Range of Control
- Ease of Control

Acceptability testing could include physical measurement of noise levels, as well as subjective (user) evaluation of the systems control features.

Table 9-1. Examples of Test Facilities for Extreme Climatic Conditions

Facility	Temperature Range	Reference
VW Climatic Wind Tunnel	-30°C to 50°C* (-22°F to 122°F) Speeds to 150 kph (93 MPH)	9-1
Fiat Climatic Test Tunnels (2)	-50°C to 50°C* (-58°F to 122°F) Speeds to 160 kph (100 MPH)	9-2
Yuma Proving Grounds	Maximums to 50°C (122°F) Mean Maximums to 41°C (106°F)	9-3
GM Kapuskasing Proving Ground	Minimum to -41°C (-42°F) Mean Minimum to -23°C (-10°F)	9-4

*A wide range of humidity control is also possible.

Reliability Testing

Systems for automotive use must be reliable under a wide variety of operating conditions. Reliability testing is often enhanced by subjecting the entire vehicle to severe operating tests such as outlined in Table 9-2. These tests usually can accelerate failure of marginal components and indicate design "weak points." Because of the importance of reliable ECS operation, reliability testing of the ECS is important.

9.2 RECOMMENDED DEVELOPMENT PROGRAM

In order to ensure timely and success development of an ECS prototype, the following major steps in the development program are important:

- Preliminary Design of the ECS
- Detailed Design of the ECS
- Construction and Testing of a Bench Model ECS
- Construction and Testing of the Vehicular ECS
- Reporting of Results

These are discussed in the following sections.

9.2.1 Preliminary ECS Design

The design of the prototype ECS should be for a specific vehicle, or group of vehicles with very similar characteristics. Results from the current work should be reviewed for their applicability to the specific vehicle and required ECS design. Most likely a new set of design calculations would be made, appropriate for the specific vehicle in question. These would serve as the basis for the detailed design.

9.2.2 Detailed ECS Design

The detailed design of the ECS would be based on specific components. The first step in preparing this design would be to acquire complete specifications on suitable components. This would include:

- Detailed Specifications
- Engineering Drawings
- Component Performance Test Results

Table 9-2. Examples of Vehicle Proving Ground Reliability Test Facilities

Facility	Test Type	Reference
Shock and Vibration Testing		
Aberdeen Proving Grounds	Belgian Block & "Burma Road"	9-5
GM Milford Proving Ground	Belgian Block	9-6
Unusual Road Conditions*		
GM Milford Proving Ground	Water Bath Gravel Road	9-6

*Including water and dust ingestion

The specifications would be used to select the desired components, develop trial designs, and arrive at the final detailed design.

The most important step in developing a detailed ECS design is to package the ECS components in the existing vehicle. This will require obtaining detailed drawings of the vehicle and the space available for the ECS components.

Two systems would be designed; a final system for eventual placement in the vehicle and an interim system for bench testing. The final system requirements would be the basis for the detailed design. The interim system would be designed as a test bed to ensure proper operation of the components as a system before the commitment to installation and testing of the ECS in the vehicle.

9.2.3 Fabrication and Testing of the ECS Bench Model

The purpose of fabricating and testing the bench model ECS, is to reduce development time and costs. Many development problems can be dealt with more readily in a controlled laboratory bench test. Also the components of the bench model system are more accessible for adjustment or modification than the components of the vehicular ECS. The cost of the additional hardware for the bench model ECS is a small fraction of the total program cost. It would be justified by overall cost savings in the development process.

Construction of the bench model ECS would begin with component acquisition. Individual components could be tested before assembly of the ECS if important performance data were needed or existing data needed verification. The bench model ECS would be constructed to duplicate the final layout as closely as possible.

The testing laboratory would need to provide suitable simulation of the vehicle's passenger compartment and the ventilation air flows. Heat transfer to ambient could be simulated with external heat sources or sinks. The battery compartment could also be simulated, but the battery ECS is a small part of the total ECS loads.

Operational tests performed on the bench model ECS should ensure its capability to meet the functional requirements with adequate margins. Preliminary criteria for acceptable noise levels, range of control, and ease of control could also be made at this time. This system could also be operated for long periods, under repeated cycling, and under simulated stress conditions to ensure reliable operation over the 3000 to 5000 hour life typical of automotive systems. Stress conditions could include shock and vibration, water and dust ingestion, etc., expected in actual operation.

Testing of the bench model ECS could reveal the need for significant design changes. In that case, the design changes would be incorporated into the bench model ECS which would then be retested.

9.2.4 Fabrication and Testing of the Vehicular ECS

Fabrication of the vehicular ECS would begin with acquisition and, if needed, testing of the system components. The final ECS unit would be assembled from these components, inspected and installed in the test vehicle. Care would be required to coordinate the ontime availability of the vehicle and ECS components.

The vehicle test program would be an extensive verification of the ECS operation, acceptability and reliability. Operational testing of the vehicle system should include:

- Heating and cooling under extreme climate conditions
- Federal Motor Vehicle Safety Standards 103 (Windshield Defrosting)
- Operation of the Battery ECS under extreme climate conditions
- Other Operational Tests Deemed Necessary

Acceptability testing should include:

- Interior Noise Levels
- Range of Control
- Ease of Control
- Interior and Exterior Emissions of Combustion Products

Reliability testing should include:

- Extended operating periods
- Repeated cycling of system operating modes

- Shock and vibration testing
- Ingestion of water and dust from vehicle operating environment

As with the bench model ECS, any resulting design changes would need to be retested to ensure a satisfactory final design.

9.2.5 Reporting of Results

Thorough documentation of the development process can avoi ..needless duplication of effort in subsequent engineering efforts. Hence, careful documentation of the basis for the final design, plus a thorough documentation of the test results, are an important part of a prototype development. Both the hardware design and the documentation should be made public and available to the electric and hybrid vehicle manufacturers when the development process has been completed.

Recommendations for future development work would be included in the final documentation and report.

9.3 ESTIMATES OF REQUIRED RESOURCE. AND DEVELOPMENT SCHEDULE

Table 9-3 summarizes the estimates of development resources and schedule. No explicit attempt has been made to estimate the costs for test facilities, but it could add considerably to the total program. Strong uncertainty about the development time needed to accomplish specific tasks also contributes to uncertainty in development costs.

The development process should take about a year. The schedule will be a compromise between extensive testing to ensure performance and the need for rapidly obtaining results useful to the Near Term Electric and Hybrid Vehicle Program.

If separate programs were required to develop the Electric and Hybrid vehicles ECS's, resources required and schedule times would be increased.

Table 9-3. Estimate of Required Resources and Schedule for Development of One ECS

Task	Engineering Labor Required (Man-Months)	Schedule Time (Months)	Total Labor Cost* ($)	Other Cost Items
Preliminary Design	2	1	16K	
Detailed Design	4	2	32K	
Bench Model ECS Fabrication & Testing	7-10	2-4	56-80K	Component Costs Test Facilities Tools & Instrumentation
Vehicular ECS Fabrication & Testing	7-12	3-5	56-96K	Component Costs Test Facilities Vehicle Use Tools & Instrumentation
Documentation & Reporting	5	2	40K	
Totals	25-33	11-14	200-264K	

*$50/hour total cost

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

Conclusions from this study cover four broad areas. These areas include:

- Development of ECS Functional Requirements
- Investigation of Potential ECS Elements
- Selection of the "Best" ECS for the Electric Vehicle
- Selection of the "Best" ECS for the Hybrid Vehicle

The details of these conclusions are covered in the following sections.

10.1.1 ECS Functional Requirements

Functional requirements for the ECS system were developed on a sound engineering basis. Appropriate engineering models were developed as the basis for calculating ECS requirements, such as heating or cooling capacity. This allowed accurate evaluation of the requirements for ECS capacity as well as an evaluation of how ECS capacity could be reduced by the use of appropriate "conservation" techniques.

Development of detailed ECS requirements necessitated breaking down the functional requirements into three major categories. These are:

- Passenger Compartment Heating and Cooling
- Windshield Defogging and Defrosting (including FMVSS 103)
- Battery Heating and Cooling

Within these major categories, further breakdowns were also needed.

<u>Passenger Compartment Heating and Cooling</u>

Thorough evaluation of passenger compartment heating and cooling loads required development of a detailed model, accounting for the following factors:

- Conduction through the vehicle body
- Solar radiation input through the windows

- Inflow of ventilating air
- Interior heat and moisture loads

Each of these loads was analyzed at the rated climate conditions. Additional analysis was performed on methods for reducing these loads by controlling and recycling ventilation air and reducing solar radiation inputs. It was found that the passenger compartment loads could be reduced to the levels given in Table 10-1.

Windshield Defrosting and Defogging

Detailed models also were constructed to evaluate the requirements for windshield defrosting and defogging. For defrosting, the model calculated the energy required to heat the window and melt the ice coating during the FMVSS 103 test. Energy losses from the window surface due to convection and radiation were also evaluated. Calculated results were confirmed by experimental data from prior studies of embedded windshield heaters. A separate model was developed to evaluate a moving air stream defroster.

Other models were developed and used to evaluate dynamic conditions for deicing and defogging. The most stringent conditions were used to develop the key defroster functional requirements as given in Table 10-2.

Battery Heating and Cooling

A separate thermal model was developed for the battery and the battery compartment. Battery temperature variation was examined under a variety of vehicle operating conditions. It was discovered that the preferred approach was to isolate the battery thermally from the ambient with a layer of insulation. This minimized battery heating and cooling loads, as indicated in Table 10-3.

Special Electric and Hybrid Vehicle Requirements

The electric vehicle was found to place few limitations on the ECS design. The relatively short operating period of the electric vehicle even allowed consideration of stored energy techniques for the ECS. However, in attempting to minimize the range penalty from ECS operation, it was decided not to use the vehicle battery as the principal ECS energy source.

Table 10-1. Summary of Range of Passenger Compartment Heating and Cooling Loads

<u>Heating Load</u> - 2.2 to 2.8 kW (7,500 to 9,500 Btu/hr)

- To maintain the passenger compartment at 18°C (65°F) with an ambient of -29°C (-20°F).

<u>Cooling Load</u> - 3.2 to 4.1 kW(11,000 to 14,000 Btu/hr)

- To maintain the passenger compartment at 25°C (77°F-40% RH) with an ambient of 49°C (120°F DB) (29°C (85°F) WB).

Note: This range of heating and cooling loads assumes reducing the ventilation flow rate to 43 to 77 m^3/hr (25 to 45 cfm) with a recirculating charcoal filter. However, the range of values used is conservative because automotive ECS's are usually designed for a -18°C (0°F) ambient for heating and a 38°C (100°F) ambient for cooling.

Table 10-2. Summary of Key Defroster Loads (Moving Air Stream Defroster)

FMVSS 103 Test ~3.4 kW (11,500 Btu/hr) for 30 minutes

Prevent Windshield Fogging ~3.2 kW (11,000 Btu/hr)

<u>Note:</u> Both of these requirements can be reduced by a third by use of a heat recovery system or use of recirculated interior air through the defroster.

Table 10-3. Summ·ʼy of Battery Heating and Cooling Lor·ᵈ

Heating Requirement - 380 watts (1300 Btu/hr) (Maximum to maintain the battery at operating temperature of 49°C (120°F) with ambient of -29°C (-20°F)

Cooling Requirement* - 120 m^3/hr (70 cfm) (Maximum air flow to maintain battery at 54°C (130 °F) during an 8 hour charge period)

*No actual battery cooling capacity is required since cooling is supplied with ambient air.

The hybrid vehicle, by contrast, can operate continuously for very long periods. The vehicle's gasoline supply proved to be the only adequate source of energy for the ECS. However, the choice of energy conversion systems for the ECS (in the cooling mode) is fairly broad.

10.1.2 Potential ECS Candidates

Potential ECS candidates were drawn from the two main categories of energy technology: energy conversion and energy storage. Energy conversion offered the widest selection of ECS elements, mainly because of the large number of heat pump cycles. These cycles included:

- Vapor Compression
- Reversed Brayton (ROVAC)
- Ericsson
- Absorption
- Jet Compression
- Hydride (Chemical)

Many alternative drives for the heat pump cycles were examined, including:

- Electric
- Otto cycle
- Stirling cycle
- Ericsson cycle
- Direct heat

Thus, a wide variety of energy conversion technologies were potentially available for the electric vehicle ECS. While a number of these systems did not meet the pragmatic requirements for this study, there were several strong contenders for the best ECS.

Energy Storage Technology

Several energy storage technologies were also investigated as the basis for ECS elements, including:

- Thermal energy storage (both sensible and latent)

- Chemical energy storage
- Absorption (heat of solution) energy storage
- Expendable refrigerants

Energy storage systems offered the potential of a low cost alternative to using fossil fuel for the ECS. However, pragmatic considerations of the total energy stored showed that the energy storage system was too heavy or too costly for electric or hybrid vehicle use. Other energy storage technologies were too early in the development cycle to be fully evaluated at this time.

Other ECS Elements

A number of other potential ECS elements found occasionally in vehicles, such as evaporative coolers and electrically heated seats, were also evaluated.

Two groups of technologies were found to be potentially useful for the electric and hybrid vehicle ECS designs. One was the solar radiation control; such as louvers, tinting and reflective window coatings, that can be used to reduce the vehicle's total solar radiation loading. Control of the solar radiation load results in lower system cooling capacity requirements.

The second group of other ECS elements included those useful in reducing the ventilation loads. This group included heat exchangers and activated charcoal filters. Heat exchangers offer the potential of recovering up to 70% of the ventilation energy loss. Charcoal filters allow sharp reduction in the ventilation rate by recirculating the interior air through the filter for odor control, thus reducing the ventilation energy loss. Charcoal filters are the most economical approach to reducing ventilation energy losses.

Waste Heat Recovery

Propulsion system waste heat potentially can be utilized as a supplement to the heat provided by the ECS heating element. In the electric vehicle, up to half the maximum heating load could be recovered from the electric motor and controller. This supplemental heat would have considerable advantage in reducing the use of primary energy by the ECS in the heating mode. Care must be taken in recovering this heat so as not to interfere with proper cooling of the propulsion system or to introduce contaminants (ozone from brush arcing) into the passenger compartment. Similarly, in the hybrid vehicle, waste heat will be available, especially from operation of the heat engine. Engine waste heat could supply all of the ECS requirements once the engine is in regular operation.

10.1.3 Best ECS for the Electric Vehicle

The combination of the combustion heating and Otto (gasoline engine) driven vapor compression cycle cooling was selected as the "best ECS" for the electric vehicle. This selection was made as part of a multiple step evaluation, designed to systematically evaluate many ECS elements and focus in a few key choices to select the "best."

The evaluation process first screened all of the ECS elements and eliminated from consideration those clearly inappropriate to the ECS requirements. A more detailed evaluation of the remaining elements was provided by a rating scheme which scored the elements on the basis of their projected cost, weight, volume, and energy requirements. Cost was the foremost consideration in the rating scheme. Elements which scored well on the rating scheme were strong contenders for the "best" ECS.

Two other factors were important in the evaluation process. One was the state of development of the ECS technology. Only technologies that were based on commercially available ECS elements or nearly developed ECS elements could be considered for the near-term ECS. The second important factor was "appropriateness for market size". Considering the limited production levels for electric vehicles that could be reasonably expected in the near term, it made "market sense" to choose existing technologies already in large scale production for the electric vehicle ECS. This was based on the observation that the automobile industry tends to minimize its risk in the introduction of new technology.

It is important to point out that the gasoline energy use by the ECS is minimal. The maximum energy use is expected to be 200 liters (57 gal.) per year or less. See Addendum A. Also, continued use of air conditioning using "freons" is not considered a major environmental problem in the near term. See Addendum B.

Figure 10-1 shows a schematic of the final arrangement for the electric vehicle ECS. The main feature of the design is the recirculating ventilation air flow for the passenger compartment. Make-up air is a fraction (43 to 77 m^3/hr or 25 to 45 cfm) of the system's full capacity (255 m^3/hr or 150 cfm). The air control valves allow the air to be directed to the defroster outlet or passenger air jets. A small amount of air can be diverted to the battery compartment as needed. A separate ventilation fan ensures positive ventilation of the battery compartment at all times. The waste heat in the drive train cooling air may be recovered as needed to supply warm make-up air. A separate air supply is used to meet the combustion air requirements of the heater and gasoline engine.

Figure 10-2 shows the details of the cooling unit. The Otto (gasoline) engine is directly coupled to the compressor. When the theromostat control senses additional cooling is needed, the electric starter engages and, causes the engine to start. The engine operates at a preset speed under governor control. The engine is stopped by turning off the ignition voltage and fuel supply.

10.1.4 Best ECS for the Hybrid Vehicle

The combination of a combustion heating system and a vapor compression cooling system was selected as the best ECS for the hybrid vehicle. The vapor compression cooling system could be driven either by an electric motor or a separate gasoline engine. If the restriction on using mechanical power directly from the vehicle's propulsion system were relaxed, then this would be the preferred means of operation. A suitable control option would be provided to "declutch" the ECS during periods of maximum load on the propulsion system, so the propulsion system's maximum power output would not need to be increased to carry the ESC load.

For long vehicle trips, when the heat engine operates extensively, provision should be made for recovering engine waste heat. This would be done by diverting a portion of the engine cooling water to a small heater core, as is done in current vehicle ECS's. Heat could also be recovered from an air-cooled propulsion engine.

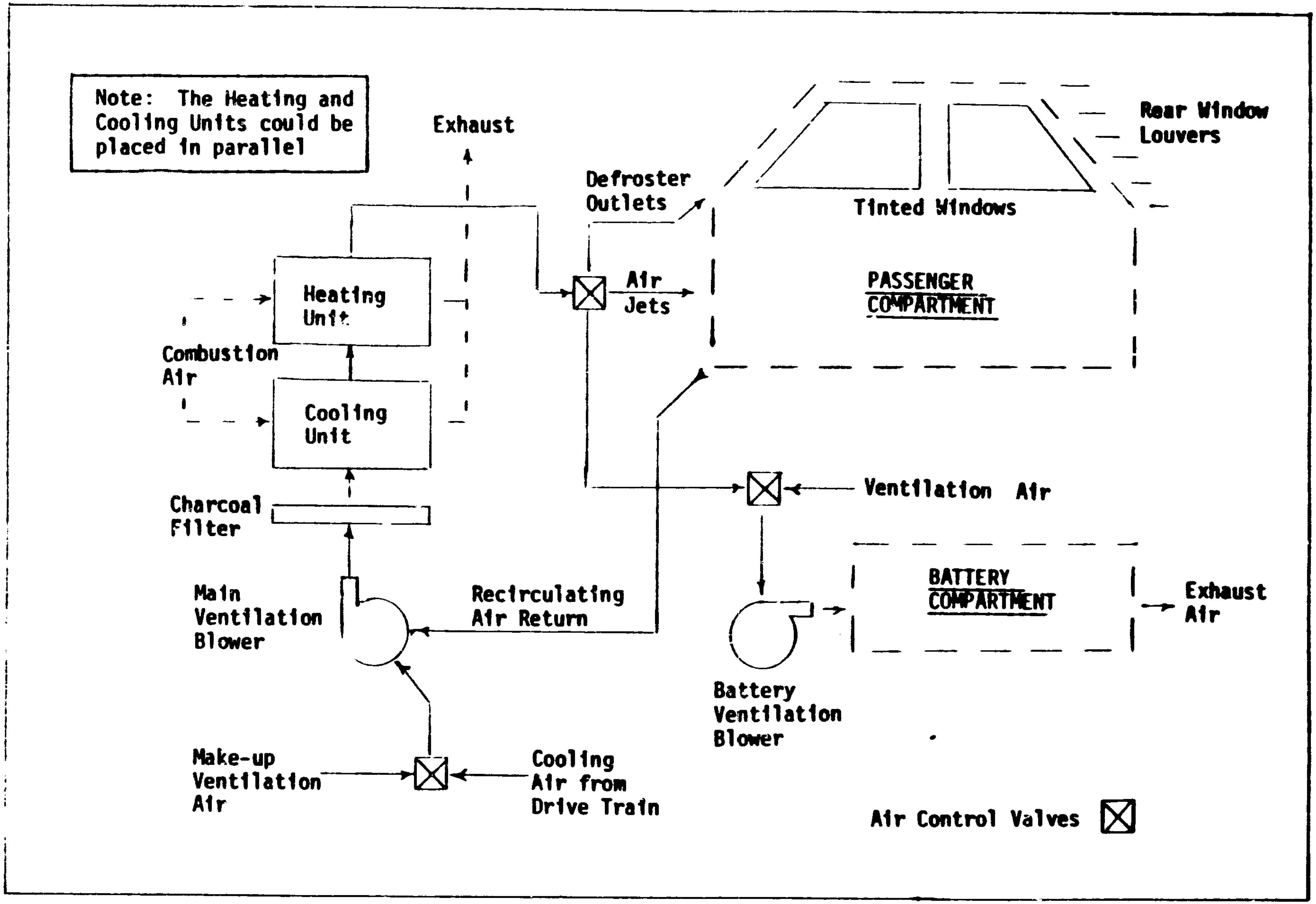

Figure 10-1. Schematic of ECS for Electric Vehicle

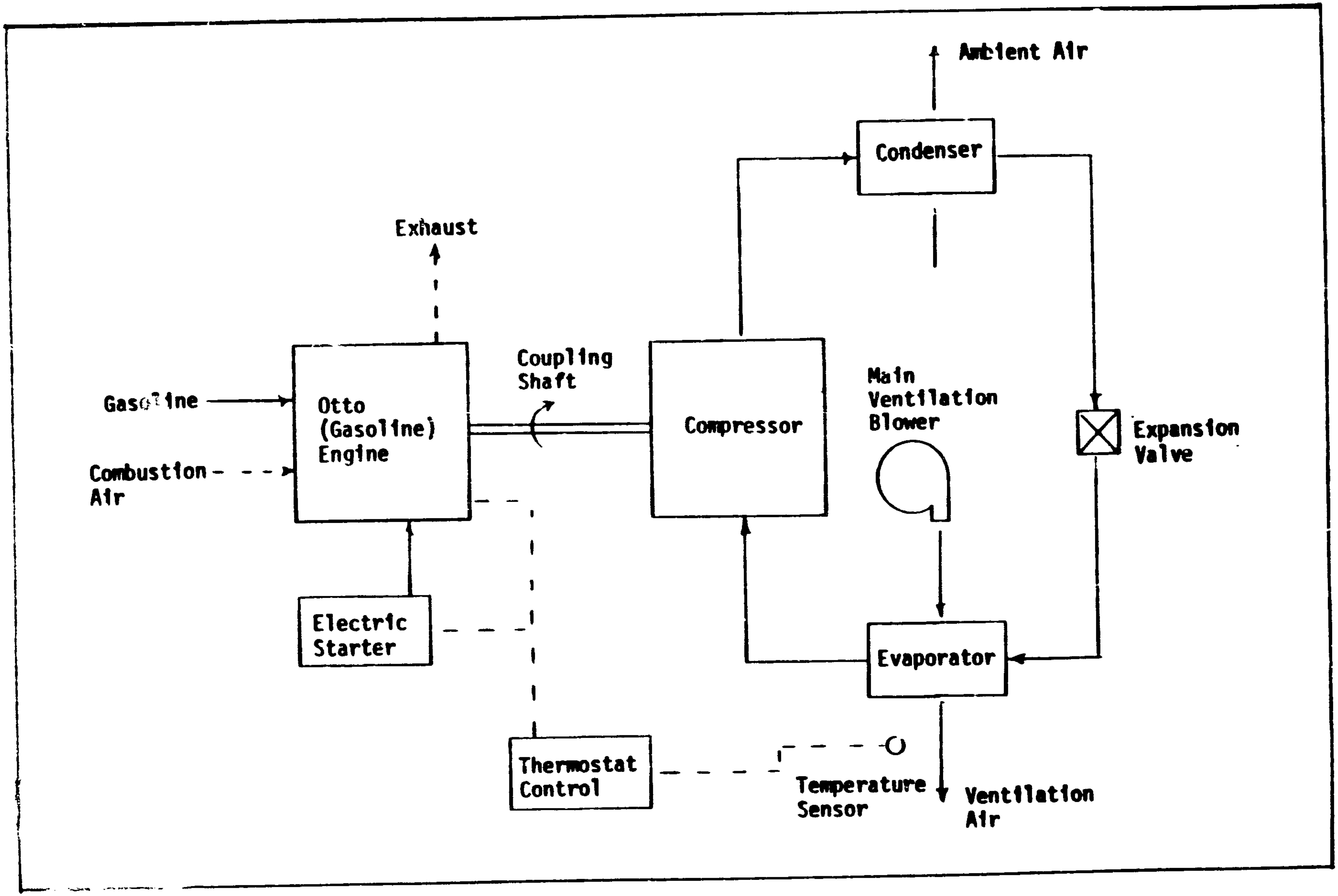

Figure 10-2. Detailed Schematic of Cooling Element

The evaluation process to select the "best" ECS for the hybrid vehicle was similar to the process used for the electric vehicle. The rating scheme was used in the same manner as in the electric vehicle evaluation to rank the alternative systems. All of the energy storage elements were eliminated as inappropraite because of the longer vehicle operating period.

An appropriate range penalty was devised for the hybrid vehicle systems based on their energy use. No formal criteria for maximum range impact was considered since the hybrid vehicle range is equivalent to current vehicles. However, systems with excessive range penalties, ie. 50%, were considered undesireable. Again, cost was the foremost consideration in the rating scheme. Elements which scored well on the rating scheme were strong contenders for the "best" ECS. State of development was also important since only near term technologies could be considered for the best ECS.

The final consideration for the hybrid vehicle ECS was appropriateness for market size. Since the hybrid vehicle is likely to be, at best, in limited production for most of the next decade, use of existing technology for the hybrid vehicle ECS is strongly suggested. Again, this is based on the observation that the automobile industry tends to minimize risks in the introduction of new technology.

Figure 10-3 shows a schematic of the final arrangement for the hybrid vehicle ECS. The system is very similar to the electric vehicle system. The main exceptions are that engine waste heat is recovered via a small radiator and that the cooling ECS can be driven electrically or mechanically, if permitted. The ECS elements are in parallel to simplify the control arrangement, though a series system is also feasible.

10.2 RECOMMENDATIONS FOR ECS DEVELOPMENT

10.2.1 Immediate Prototype Development

Electric Vehicle ECS

It is recommended that the development of the electric vehicle ECS be given priority. This is because electric vehicle development is much more advanced than hybrid vehicle development. There is a considerable current market and an even larger potential market for an electric vehicle ECS.

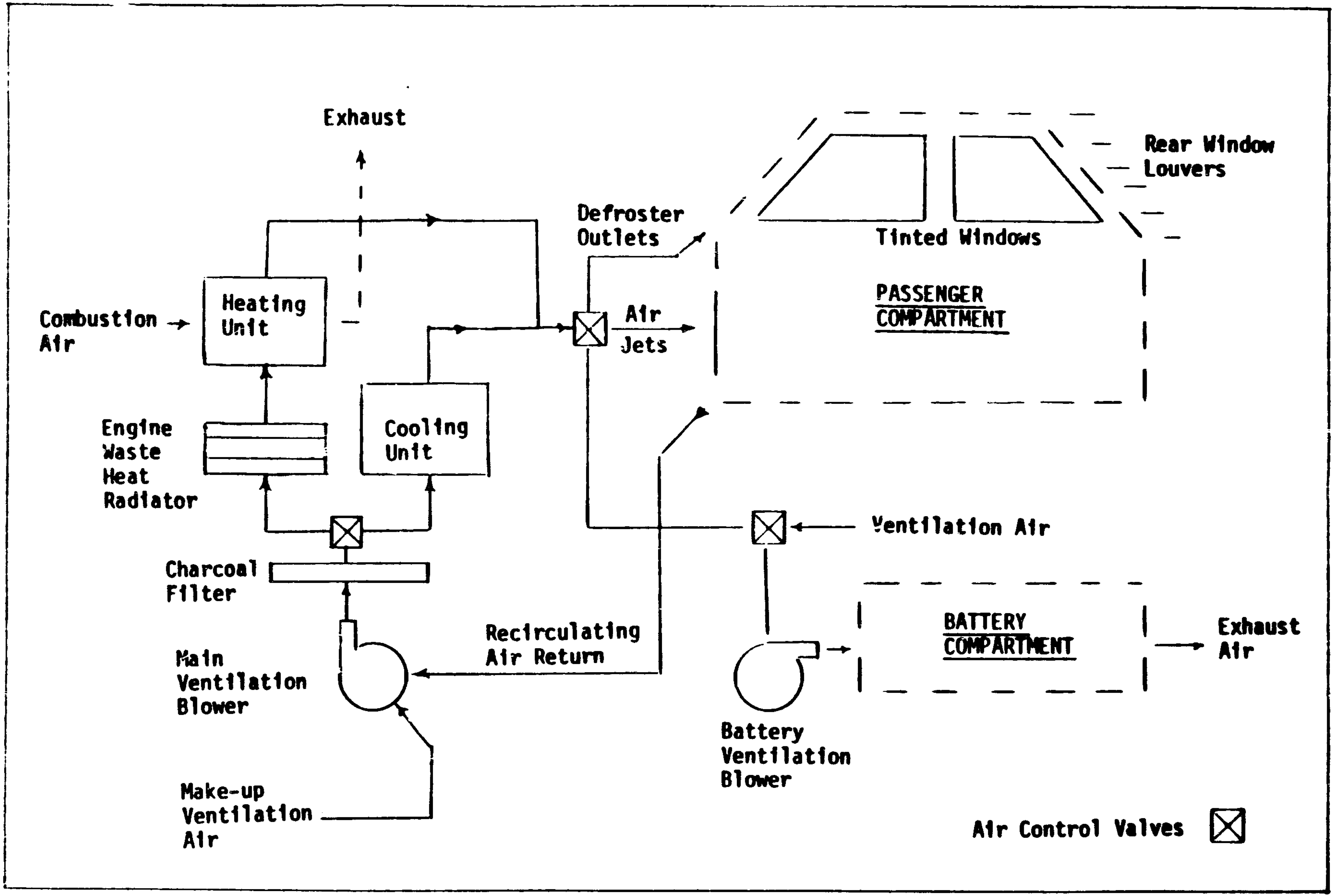

Figure 10-3. Schematic of ECS for Hybrid Vehicle

The system for immediate prototype development should be the combustion heater and gasoline engine driven vapor compression cooling. The ECS development should include modification of the vehicle with tinted windows and rear window louvers to reduce inputs from solar radiation. The ECS should also utilize an activiated charcoal filter to reduce the requirements for ventilation air by recirculating interior air through the charcoal filter for odor control.

Hybrid Vehicle ECS

The hybrid vehicle "best" ECS is very similar to the electric vehicle "best" ECS, as well as to ECS's in current vehicles. Hence, the electric vehicle ECS development will incorporate most of the features required for the hybrid vehicle.

More likely, it would be best to consider incorporating the results of this study in the development of the ECS for the current Phase II Near-Term Hybrid Vehicle. The Phase I design for this vehicle (Reference 8-2) already incorporates such features as:

- A combustion heater, supplemented by engine waste heat during engine operation
- A mechanical takeoff for operating the vapor compression cooling system (or other heat pump cycle)

Most likely, it would be best to continue development of the vehicle with this system, incorporating where possible features for reduction of solar radiation and ventilation loads in the vehicle design.

10.2.2 More Extensive Prototype Development

Certain technologies potentially offer ECS designs that would be more efficient, as well as smaller and lighter. Based on the data available to this study, the Ericsson Ericsson and Electric Ericsson cycles, under development by Energy Research and Generation (Reference 4-5), appear to be the most attractive. However, because of the uncertainty surrounding vehicle technology from factors such as

- Improvements in battery technology
- Future fuel and electricity prices
- Relative market penetration of electric and hybrid vehicles,

a specific program of technical development cannot be recommended. Research efforts should be focused on obtaining detailed characterizations of attractive advanced heat pump technologies. Data from such characterizations would allow clearer decisions to be made about specific product developments utilizing these technologies at a future date.

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ADDENDUM A

ANNUAL ENERGY USE FOR BEST ECS

The annual energy use for the ECS can be estimated on the basis of average ambient temperatures. Figures A-1 and A-2 gives the variation in heating and cooling load respective with temperature. This data was used in Tables A-1 and A-2 to calculate the average heating and cooling loads. Appropriately severe climates were used for both load calculations. Additional allowance was made for defrosting the windshield in the winter climate. The conclusion is total ECS annual gasoline use should be under 52 gallons per year for the electric vehicle. Similar results would be expected for the hybrid vehicle.

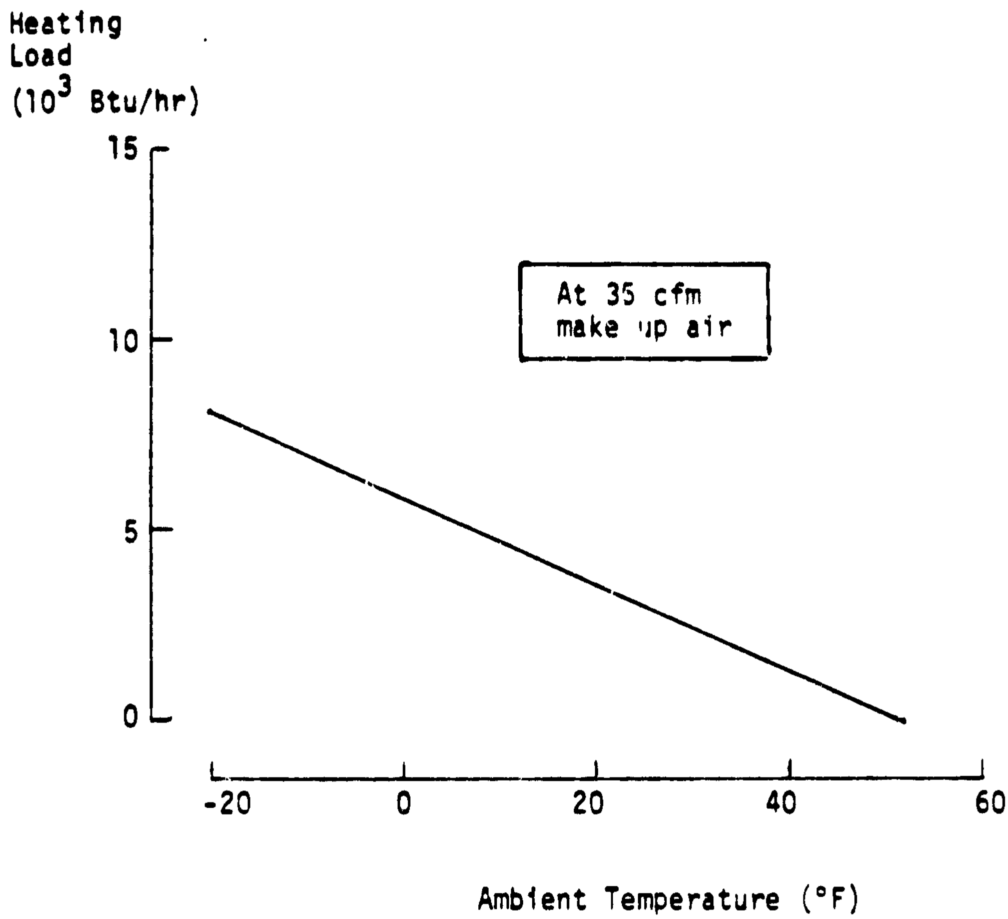

Figure A-1. Heating Load Versus Ambient Temperature

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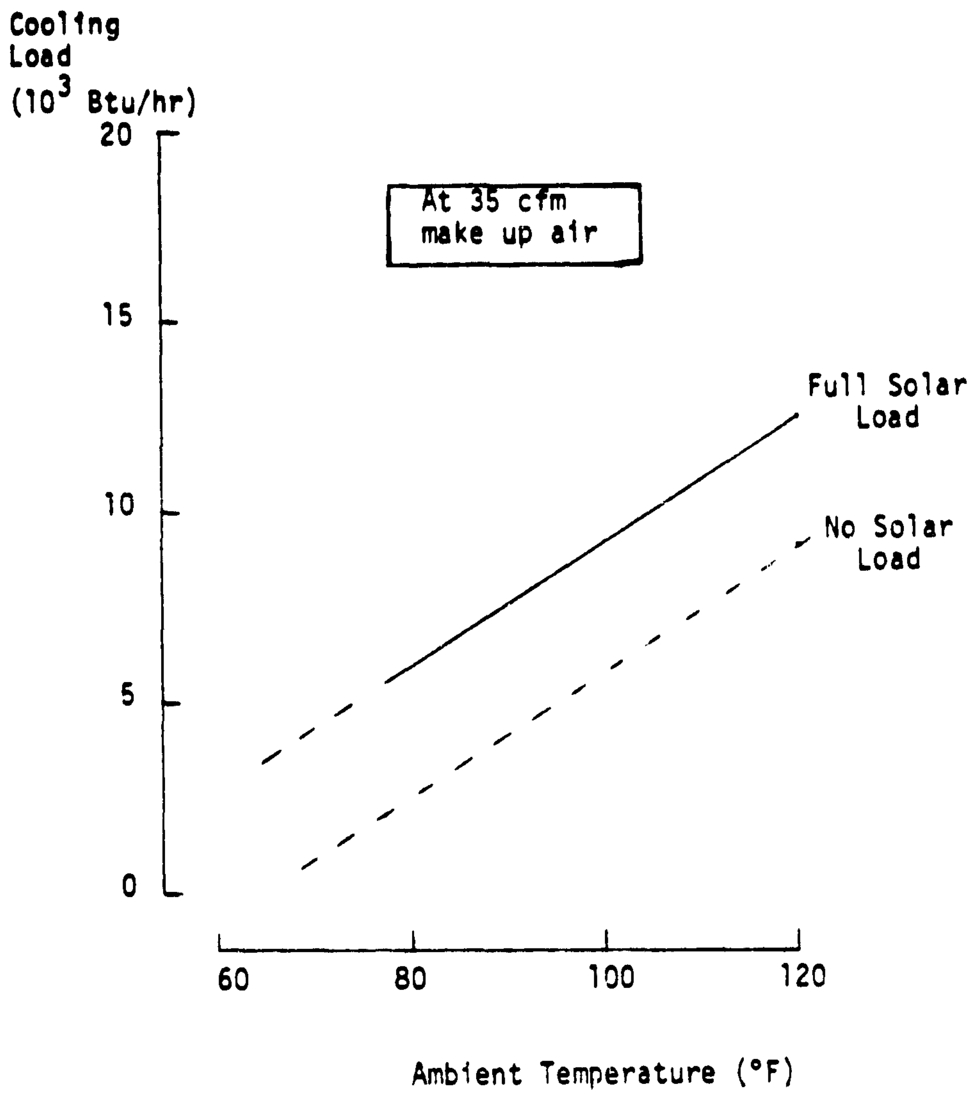

Figure A-2. Cooling Load Versus Ambient Temperature

Table A-1. ECS Annual Energy Use for Heating in Bismark, N.D.

Average Winter Capacity Calculation

Month	Average Temp (°F)	Heating Capacity (Btu/Hr)
October	47	500
November	29	2300
December	16	3700
January	8	4500
February	14	3900
March	25	2700
April	43	800
	Average Capacity	2600 Btu/hr

Assumed monthly operation = 50 hours

Total winter heating energy = 910,000 Btu

Estimated energy for 100 windshield defrosts at 6000 Btu per defrost = 600,000 Btu

Input at 75% efficiency = 1.8 MMBtu
or 14 gallons of gasoline

Table A-2. ECS Annual Energy Use for Cooling in Phoenix, AZ

Average Summer Capacity Calculation

Month	Average Temp (°F)	Cooling* Capacity (Btu/hr)
April	67	4200
May	81	6100
June	88	7300
July	94	8200
August	93	8000
September	85	6800
October	74	5000
	Average Capacity	6500 Btu/hr

Average input energy required = 20,280 Btu/hr

Assumed monthly operation = 50 hours

Total summer cooling energy = 7 1 MMBtu
or 52 gallons of gasoline

*Full solar load

ADDENDUM B
POTENTIAL RESTRICTIONS ON USE OF FREONS

Scientific investigations concerning the potential depletion of stratospheric ozone by halocarbon emissions have lead to discussion of ways of reducing halocarbon emissions. One potential measure discussed is restriction on the use of halocarbons in particular chlorofluoro methanes (CFMs). However, nearly 50% of all CFMs are used as aerosol propellants, while only about 25% are used as refrigerants. Thus, in the near term, reducing use of CFM's as aerosols would be a more effective control measure than restricting their use in heat pump systems.

Source: "Stratospheric Ozone Depletion by Halocarbons: Chemistry and Transport." National Academy of Sciences, Washington, D.C. 1979.