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NONTOXIC HEAT TRANSPORT FLUIDS FOR SPACECRAFT TWO-PHASE THERMAL CONTROL SYSTEMS

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NOMENCLATURE AND DEFINITIONS

Nomenclature

C_p	Specific heat at constant pressure, J/(kg-K)
D	Diameter, m
F	Correction factor in Chen boiling correlation
G	Mass velocity, kg/(s-m^2)
ΔH	Latent heat of vaporization, J/kg
h	Heat transfer coefficient, W/(m^2-K)
k	Thermal conductivity, W/(m-K)
L	Length, m
LTF	Liquid transport factor, $\sigma\rho_l\Delta H/\mu_l$, W/m^2
ΔP_{sat}	$P_{sat,Twall} - P_{sat,Tbulk}$, Pa
PCRIT	Critical pressure, Pa
Pr	Prandtl number=$C_p\mu/k$
PRED	$PVAP/P_{crit}$
PVAP	Vapor pressure at T_{bulk}
Re	Reynolds number=DG/μ
S	Correction factor in Chen boiling correlation
ΔT_{sat}	Wall superheat = $T_{wall} - T_{bulk}$, K
TCRIT	Critical temperature, K
TRED	T_{bulk}/T_{crit}
v	Specific volume, m^3/kg
WF	Weight factor
WFDEN	Ranking factor for the liquid density
WFFOMB	Ranking factor for figure of merit for boiling
WFLTF	Ranking factor for the liquid transport factor
WFNBP	Ranking factor for normal boiling-point temperature
WFPVAP	Ranking factor for vapor pressure at the bulk temperature
WFTMP	Ranking factor for the normal melting-point temperature
x	Quality (mass fraction vapor)
χ_{tt}	Martinelli-Nelson correlating parameter
α	Volume fraction vapor
μ	Viscosity, (N-s)/m^2 or Pa-s
ρ	Density, kg/m^3
σ	Surface tension, N/m
Φ_l^2	Two-phase friction multiplier based on pressure gradient for liquid-alone flow
Φ_{lo}^2	Two-phase friction multiplier based on pressure gradient for total flow, assumed liquid

Coefficients in Equations (A9) and (A10)

AF = -0.188 321 1071E+02
BF = 0.580 694 7612E+01
CF = -0.551 671 5499
DF = 0.166 927 8595E-01

AS = 0.994 610 2006
BS = 0.591 353 4234
CS = 0.554 849 7826E-01
DS = -0.586 330 4243E-02

Subscripts

bp	boiling-point
bulk	evaluated at bulk (saturation) conditions
c	convection
cond	condensation
crit	critical
f	liquid
g	vapor, gas
l	liquid
mix	two-phase mixture
mp	melting-point
NuB	nucleate boiling
red	normalized by critical property
sat	saturation
tp	two-phase
tt	turbulent-turbulent
v	vapor
wall	evaluated at wall temperature

Definitions

Coefficient of Performance for Boiling (COPB)-
Ratio of the heat flux required to completely vaporize the liquid, flowing at a fixed Reynolds number, to the pumping power per unit surface area required to move the fluid through the pipe for a fixed L/D and D.

Coefficient of Performance for Condensation (COPC)-
Ratio of the heat removed to completely condense the vapor, flowing at a fixed Reynolds number, to the pumping power per unit surface area required to move the fluid through the pipe for a fixed L/D and D.

Density of the Liquid (DEN)-
Density of the liquid at the bulk temperature and corresponding vapor pressure, kg/m^3.

Figure of Merit for Boiling (FOMB)-
Ratio of an integrated-average forced-convection boiling-heat-transfer coefficient in a pipe, over the length of which complete vaporization of the liquid stream occurs due to the application of a uniform heat flux, to the pumping power per unit surface area required to move the two-phase fluid through the pipe, $(W/m^2\text{-}K)/(W/m^2)=1/K$.

Figure of Merit for Condensation (FOMC)-
Ratio of an integrated-average forced-convection condensation-heat-transfer coefficient in a pipe, over the length of which complete condensation of the vapor stream occurs due to the removal of heat, to the pumping power per unit surface area required to move the two-phase fluid through the pipe, 1/K.

Liquid Transport Factor (LTF)-
Ratio of properties (see nomenclature) that compares the relative merits of the fluids for use in heat pipes in a low-gravity field, W/m^2.

Melting-point (TMP)-
Temperature at which a solid melts at 101 kPa (1 atm), K.

Normal Boiling-point (NBP)-
Saturation temperature at 101 kPa (1 atm), K.

Operating Pressure (PVAP)-
Vapor pressure at the bulk temperature within the temperature range, Pa.

Ranking Factor (WF****)-
Value denoting the proximity to the preferred value for the parameters FOMB, NBP, PVAP, TMP, LTF, DEN (may have a value from 0 to 1 and the **** may be FOMB, NBP, etc.).

Weight Factor (WF)-
Assigns a number to the relative importance of each parameter considered relevant to the evaluation of a fluid.

Conversion of SI Units to Engineering Units

To obtain	from	multiply by
Atm	Pa	9.860×10^{-6}
Btu/lb_m	J/kg	4.2992×10^{-4}
$Btu/(lb_m-{}^oF)$	J/(kg-K)	2.3885×10^{-4}
$Btu/(h-ft^2-{}^oF)$	$W/(m^2-K)$	1.7612×10^{-1}
$Btu/(ft^2-h)$	W/m^2	3.1726×10^{-1}
cP	Pa-s	1×10^{3}
ft	m	3.2808
lb_f/ft	N/m	6.8522×10^{-2}
lb_f/ft^2	Pa	2.089×10^{-2}
lbm/ft^3	kg/m^3	6.248×10^{-2}
${}^oF$	K	$t_F=1.8t_K - 459.67$
${}^oF$	${}^oC$	$t_F=1.8t_C + 32$

SUMMARY

A search was conducted for an environmentally acceptable heat transport fluid for use in a two-phase thermal control bus of a manned spacecraft. A fluid having the following general characteristics was sought: (1) nontoxic, (2) nonflammable, (3) noncorrosive, (4) having long-term stability, (5) catalytic decomposition resistant (at temperatures of the order 573 K), (6) possessing optimum physical properties for efficient forced convection boiling heat transfer, and (7) having a vapor pressure near 101 kPa (1 atm) at room temperature.

The approach was to (1) develop a methodology to evaluate and rank potential candidates for which thermodynamic and transport properties were available, (2) perform the evaluation for a wide range of fluids, and (3) survey the commercial suppliers to establish the availablity or unavailability of a suitable fluid.

The candidate fluids were restricted to those that could operate in a two-phase system within certain temperature ranges. The ranges were selected to cover temperature extremes anticipated to exist in the internal and external thermal control loops being considered for the thermal bus of the Space Station.

Temperature range (1): freezing point less than 198 K (-75^{o}C) and a critical temperature greater than 348 K (75^{o}C).

Temperature range (2): freezing point less than 273 K (0^{o}C) and a critical temperature greater than 322 K (49^{o}C).

Many of the common refrigerants and hydrocarbons emerged as top-ranked fluids for thermal performance and other relevant parameters defined in our study. However, none of these fluids met all the other stringent requirements of nontoxicity, nonflammability, and stability at high temperatures. Further, the responses from commercial suppliers , queried world-wide, revealed no commercially marketed heat transport fluid that satisfies all specified requirements.

Based on the results of the study, we recommend the following:

1. Investigate the feasibility of the development of a new substance.

a. In order to more clearly specify the range of thermodynamic and transport properties desired, complete a more detailed statistical analysis of the relationship between the physical properties and FOMB. This should be done in consultation and cooperation with chemists

contemplating the possible molecular structures for the fluid.

2. Investigate the possibility of using a mixture of existing fluids.

3. Investigate the catalytic converter technology for possible new concepts that would eliminate the high temperature thermal stability constraint on the candidate fluid.

NONTOXIC HEAT TRANSPORT FLUIDS FOR SPACECRAFT TWO-PHASE THERMAL CONTROL SYSTEMS

NASA Contract T-4528P

Patricia J. Giarratano, James F. Welch

This report summarizes an investigation to determine the availability of a nontoxic, nonflammable, noncorrosive and thermally stable heat transport fluid suitable for two-phase thermal control systems in manned spacecraft. Approximately 860 chemical substances were sorted and ranked according to parameters that were defined and calculated to quantitatively evaluate fluids for the proposed application. A methodology was developed for the evaluation and ranking. A survey of world suppliers of heat transport fluids was also conducted to determine whether a suitable fluid is available. The investigation did not identify a fluid that can meet all the environmental and thermal property requirements required for safe and efficient performance in the spacecraft application.

Key words: commercial heat transport fluids; heat transport; nontoxic fluids; spacecraft; thermal control; two-phase

INTRODUCTION

The Center for Chemical Engineering of the National Institute of Standards and Technology conducted a search for alternative nontoxic heat transport fluids for two-phase thermal control systems for spacecraft, particularly those serving life support systems or crew module systems. The low vapor pressure of water, 2.48 kPa (0.36 psia) at 294 K (21^{o}C), and the relatively high freezing temperature (273 K) make this otherwise desirable (from the point of view of toxicity and other handling characteristics) heat transport fluid less than ideal for the manned modules of spacecraft if a failure condition should occur. The low vapor pressure favors air leakage from the crew modules into the thermal bus and thereby impairs operation of the system. Water's relatively high freezing point may result in "freeze-up" during "off-normal" conditions.

The high temperature catalytic converter in the crew compartment presents an additional constraint on the selection of the heat transport fluid for the thermal bus.

A suitable fluid must not be subject to catalytic decomposition into toxic substance(s) when exposed to temperatures in the order of 573 K (300^{o}C).

Ultimately the development of a new, nontoxic, nonflammable, stable heat transport fluid specifically for the spacecraft application may be required. However, in view of the likely high cost and complexity of the development and testing of such a fluid, NASA requested an extensive evaluation of existing substances, including commercially marketed heat transport fluids, to establish the need and/or specifications for the possible development.

Our approach to the problem was to develop a methodology to provide a basis for quantitative evaluation of potential heat transport fluids and apply the method to rank existing fluids according to a weighted sum of relevant parameters which are defined in the text. The emerging top ranked fluids could then be subsequently evaluated for environmental characteristics, including, for example, toxicity, flammability, and thermal stability. The methodology requires that the thermodynamic and transport properties of saturated liquid and vapor at the operating temperature be specified. Given these properties, the method can be applied to predict the performance of existing or new fluids which may be developed for the proposed application.

The parameter assigned the highest weight in the ranking procedure was the thermal performance of the fluid. This was defined as the ratio of an integrated average film coefficient of heat transfer to the power consumed in circulation through a uniformly heated (or cooled) pipe. A similar approach for evaluation of media for single-phase heat transfer systems was suggested by Parsons et al.[1] and Carberry[2]. We applied the method to a simple two-phase heat transfer system which is defined in the text and appendix.

This study is concerned with the thermal control systems for mannned spacecraft. A similar independent study has recently been completed by McLinden[3] in which the evaluation of fluids for two-phase heat transport was performed for unmanned spacecraft application (for example, external thermal control loop for Space Station). The results of the two investigations are consistent.

While the fluid property database that we employed in the study is extensive (860 substances), it is not all-inclusive; therefore, a survey of known commercial suppliers of heat transport fluids was conducted to ascertain the availability of suitable fluids that were not in the computer database.

APPROACH

An outline of the method employed in this study follows:

(1) Obtain computer database of themodynamic and transport properties of fluids.

(2) Select fluids for evaluation.

(3) Rank the fluids according to a composite of the ratio of heat transfer to pumping power, normal boiling-point, vapor pressure at the selected operating temperature, freezing point, liquid transport factor and density.

(4) Obtain toxicity, flammability and other handling characteristics for top ranked fluids and eliminate unsuitable materials.

(5) Contact commercial suppliers of heat transport fluids for information on substances not contained in the property database.

Computer Database

The thermodynamic and transport properties for approximately 860 fluids were obtained from the Physical Property Data Service (PPDS)[1] computer Electronic Data Module [4]. This database contains a wide variety of fluids, selected for their industrial importance. It is particularly strong in the hydrocarbon and simple organic (< 4 carbons) fluids. The following fluid properties for saturated liquid and vapor and physical constants were obtained for a range of temperatures of interest:

(1) Density
(2) Heat capacity
(3) Latent heat of vaporization
(4) Thermal conductivity
(5) Viscosity
(6) Surface tension
(7) Vapor pressure
(8) Molecular weight
(9) Critical temperature
(10) Critical pressure
(11) Melting-point
(12) Normal boiling-point.

[1] We use trade names to specify the computer database adequately and do not imply endorsement by the National Institute of Standards and Technology. Similar products by other suppliers may work as well or better.

If any of these properties of a fluid were not available in the PPDS database at the temperature of interest, then that fluid was not included in the evaluation at that temperature.

Selection of Fluids for Evaluation

A review of prior NASA reports, [5-7], and discussion with NASA JSC personnel established the range of temperatures of interest. The evaluation of fluids was limited to those that have:

Temperature Range (1): a freezing point less than 198 K (-75°C) and a critical temperature greater than 348 K (75°C) or

Temperature Range (2): a freezing point less than 273 K (0°C) and a critical temperature greater than 322 K (49°C).

For the Space Station application, Temperature Range (1) represents a range of temperature that covers both internal and external thermal bus loop operating temperature extremes. That selection criterion reduced the number of fluids from 860 to 330.

Temperature Range (2) represents a narrower range of temperature that covers the internal thermal bus loop operating temperatures. This less restrictive temperature range was satisfied by 659 fluids.

Rank Fluids Falling within the Temperature Ranges

Without regard to fluid toxicity or other handling characteristics, we defined six parameters that provide the basis for a quantitative evaluation/ranking of the fluids. The parameters are evaluated at four different temperatures within each range (200, 250, 300, and 350 K for Temperature Range (1); 275, 290, 305, and 320 K for Temperature Range (2)). The ranking parameters are:

(1) Ratio of an integrated-average forced-convection-boiling heat transfer coefficient in a pipe, over the length of which complete vaporization of the liquid stream occurs due to the application of a uniform heat flux, to the pumping power per unit surface area required to move the two-phase fluid through the pipe. (FOMB, see appendix for details.) This quantity characterizes the thermal performance capability of the fluid. A high value is preferred.

(2) Operating pressure (PVAP - vapor pressure at each of the four bulk temperatures within the temperature ranges). This quantity influences the pipe wall thickness which in turn influences the mass of the system. A favorable ranking is assigned to fluids having a vapor pressure equal to 101 kPa (1 atm). That operating pressure would minimize the potential for leakage into or out of the crew cabin module.

(3) Normal boiling-point (NBP - the saturation temperature at 101 kPa). A favorable ranking is assigned to fluids having a normal boiling-point near 293 K (20^{o}C).

(4) Freezing point (TMP). A low value avoids the possibility of freeze-up. A favorable ranking is assigned to fluids having a low freezing point.

(5) Liquid transport factor (LTF). This factor is used to compare the relative merits of the fluids for use in heat pipes in a zero-gravity field [8]. A large value of LTF is preferred in the ranking scheme.

(6) Liquid density (DEN). This quantity, like operating pressure, influences the mass of the system. All other criteria being equal in a ranking scheme, the lower density receives a more favorable ranking.

Calculate Relative Ranking, WF**, of Each Fluid for Each Parameter**

For each parameter, a ranking of each fluid is calculated on the basis of its proximity to the preferred value for that parameter. For example the fluids having the highest value of FOMB are given a ranking factor of 1, while the fluids having the lowest values of FOMB are given a ranking factor of 0 (or a very small number). The ranking factors were calculated using the statistical technique of calculation of cumulative relative frequency [9]. This procedure eliminates the need to scan the entire column of data to determine a fluid's relative ranking within the column. It also provides a means of placing the parameters on the same basis so that an overall ranking of a fluid may be obtained by addition of the ranking factors for all parameters. See the appendix for more detail on calculating ranking factors within each parameter column.

Assign a Weight Factor to Each of the Ranking Parameters

In order to assess the overall potential of a fluid as a candidate alternative heat transport fluid, we have assigned weight factors to the six parameters according to our estimate as to the relative importance of that parameter in the overall ranking. The weight factors assigned are:

Parameter	Weight factor
FOMB	1.0
NBP	0.5
PVAP	0.4
TMP	0.3
LTF	0.2
DEN	0.1

With the above scheme, the maximum total ranking factor possible for any fluid is 2.5; that is,

```
TOTAL = 1.*WFFOMB + 0.5*WFNBP + 0.4*WFPVAP +
        0.3*WFTMP + 0.2*WFLTF + 0.1*WFDEN
```

where the individual ranking factors ,WF****, (*=any letter in the parameter acronym) may be any value from 0 to 1. Since TOTAL is determined near the final stage of calculations, it would be straightforward to redo the calculation with different weight factors if others are suggested in the future.

Auxilliary Parameters

Additional parameters which we consider to be ancillary to the parameters described above were calculated but they provide supplementary information for the ranking process. The parameters (see appendix for calculation details) are:

(1) Ratio of integrated-average forced-convection condensation-heat-transfer coefficient to the pumping power required to move the two-phase fluid through the bus. (FOMC - figure of merit for condensation.)

(2) Ratio of the heat flux required to completely vaporize the entering liquid, flowing at a fixed Reynolds number (2000 or 200 000), to the pumping power per unit surface area required to move the fluid through the pipe for a fixed L/D and D (COPB - coefficient of performance for boiling). In an analagous fashion, the ratio of the heat flux removed to completely condense the entering vapor, flowing at a fixed Reynolds number (2000 or 200 000), to the pumping power per unit suface area required to move the fluid through the pipe for a fixed L/D and D (COPC - coefficient of performance for condensation). Note:COPB = COPC.

(3) The temperature difference at the pipe exit between the inside pipe wall surface and the bulk fluid (DELTB = $\nabla T_{boiling}$, DELTC = $\nabla T_{condensation}$) for complete vaporization or condensation occuring in the pipe, respectively.)

Survey Commercial Suppliers of Heat Transport Fluids

Names of potential commercial suppliers of heat transport fluids were compiled from a variety of sources [10-12]. Each of the companies was contacted by telephone or letter requesting information on its products which might meet the specified requirements. The list of companies contacted and sample survey letters are included in the appendix.

RESULTS AND DISCUSSION

Results of Existing Fluids Study (PPDS)

The final ranking of the fluids in the PPDS database and separation into categories of Temperature Ranges 1 and 2 are shown in Tables 1-4 and 5-8, respectively. Only the top ranked (approximately fifty) fluids are presented for conciseness. The rankings are for Re=2000 (the classical Re where turbulent flow in a pipe commences) and L/D=100, D=0.02 m. Results for Re=200 000 were also obtained but because the rankings were not significantly different from those at Re = 2000 for the same T_{bulk}, they are not presented. A complete ranking of all fluids within the temperature ranges at both Re numbers was delivered to NASA in a Progress Report completed earlier. Tables 1-8 list in decending order of total ranking number, TOTAL (max possible = 2.5), the PPDS identity number (IDN), the chemical formula and abbreviated name (SPECIES), and the relative ranking factors (WF****) for the parameters defined in the previous sections.

The weighting of the parameters and the assumption of a linear weighted sum was arbitrary. However, for the assumptions noted in the text in this regard, we can observe the fluids that have the toprankings.

Many of the refrigerants (for example, IDN 485-difluoromethane, 431-dichlorodifluoromethane, 492-difluoroethane, 369-chlorodifluoromethane) emerge as top ranked fluids for all the bulk temperatures. This is not surprising since these substances were specifically developed as heat transport media. However, as was pointed out by previous NASA investigations [5], these substances are subject to decomposition into toxic gases if subjected to high temperatures such as in a crew-cabin catalytic converter.

Hydrocarbons (for example IDN 58-propene, 57-propane, 6-butadiene, 60-propyne) also rank high among the fluids tested, but because of their flammability, are not considered a viable option.

Although we have not examined in detail the toxicity, chemical stability or handling characteristics of the top ranked fluids, there does not appear to be any substance contained in the two temperature ranges that will emerge as a candidate fluid for use in the manned spacecraft thermal control systems. The top ranked fluids are either toxic (either upon decomposition or outright) or flammable, or both.

Table 9 was prepared from the complete ranking listings which are not included in this final report. The table illustrates how water and ammonia (fluids proposed for the internal and external thermal bus loops of Space Station) rank in the two temperature ranges, according to thermal performance. We note that water (IDN 63) is ranked near the bottom of the list for all the bulk temperatures in Temperature Range 2, although the ranking improves as the temperature increases to 320 K. This ranking, in spite of its attractiveness from the the point of view of toxicity and handling, substantiates NASA's desire to replace it in future thermal control system designs. Further, ammonia (IDN 70) currently earmarked for use in the external thermal control loop of Space Station ranks fairly high in the list of fluids for both Temperature Ranges 1 and 2. The high ranking, however, is offset by ammonia's unattractive environmental and toxicological properties.

We mentioned in the introduction that McLinden[3] performed an independent but similar investigation of "working fluids for space-based two-phase heat transport systems." His approach differed somewhat from ours, as his rating factors were based on incremental system weights (or differences in system weights between fluids) which arose because of, for example, fluid weight, fluid dependent portion of components weights, and an allowance for pumping power. However, all but six of the 52 fluids top ranked in McLinden's scheme appeared in the list of top ranked fluids in our study even though the absolute order of the ranking was not identical. Ammonia was ranked as the most favorable fluid and water as the least favorable (Table 4 of McLinden's report). The results of the two studies are not inconsistent.

The functional relationship between fluid properties and thermal performance ranking is complex. We observed a correlation between low liquid viscosity and high ranking for thermal performance. We expect this since a low viscosity results in lower frictional pressure drop and correspondingly lower pumping power. None of the other properties show a pattern that would lead to a similar statement except for proximity to thermodynamic critical point. In general the fluids that rank the highest at a given bulk temperature are nearer their thermodynamic critical point than the lowest ranked ones. This can be

verified by noting the product of reduced temperature ($TRED=T_{bulk}/T_{crit}$) and reduced pressure ($PRED=PVAP/P_{crit}$) in Table 10. A value of 1 indicates the thermodynamic critical point. The fluids ranked highest appear to have the highest value of this product; conversely, the lowest ranked fluids have the smallest value. For supercritical fluids, the correlation between proximity to thermodynamic critical point and enhanced heat transfer coefficient has been demonstrated [16]. A plot of the properties parameters that occur in various single-phase forced-convection heat transfer correlations peaks near the critical point (or transposed critical points which exist above the critical pressure). The peak is made evident by enhanced heat transfer coefficient. For the subcritical fluids and two-phase heat transfer correlations of this study this seems to be the case also. More extensive review and statistical analysis would be required to substantiate the relationship between proximity to critical point and high ranking. Since FOMB (the value of which is related to the heat transfer coefficient) is weighted the heaviest, the higher ranking for fluids more near thermodynamic critical point is also reflected in Tables 1-8. Further, the variation of proximity to critical with temperature probably accounts for the differences in ranking of the fluids for the different bulk temperatures.

Again, because of the complexity of the functional relationship between the properties parameters and heat transfer coefficient (for forced convection boiling) a detailed statistical analysis is required. Therefore, it is difficult to specify the properties of an "ideal" fluid which can be used as a basis for the development of a new heat transport fluid without further analysis.

Results of Commercial Survey

A summary of some of the responses from manufacturers of heat transport fluids is contained in Table 13. Not all those contacted responded to the survey and in general property data supplied was not sufficient to rank the fluids quantitatively. However, as can seen from Table 13, the primary obstacles to meeting the NASA requirements are that the vapor pressure is low at room temperature and/or the substances are toxic, flammable, or subject to decomposition at high temperature, or a combination of all these. None of the responses was encouraging enough to pursue detailed property data for quantitative evaluation and ranking.

CONCLUSIONS AND RECOMMENDATIONS

This study leads to the conclusion that there is a need to develop a nontoxic, nonflammable, stable heat transport fluid for application to manned spacecraft . The following outline is suggested for consideration:

Develop a New Substance

A more detailed statistical analysis of the relationship between dominant physical properties and heat transfer coefficient and pressure drop in the correlations for two-phase forced-convection heat transfer is recommended. The database and tools developed in this study can be applied in this step. The analysis may provide guidance in the development of a new optimum heat transport fluid, should the development be feasible.

Since nontoxicity, nonflammability and chemical stability at high temperatures are the qualities which are missing from all the "good thermal performers," studies to formulate candidate molecular structures having these attributes are also recommended. Concurrent with this phase the thermophysical properties of the proposed molecular structure may be predicted using well-known group contribution techniques or other suitable methods. The methodology developed in our current study could then be applied to rank the candidate fluid. A computerized expert system could also be implemented to aid the likely iterative process that will be necessary to zero in on a candidate molecular structure.

Investigate the Possibility of Using a Mixture of Existing Fluids

Establish a list of candidate nontoxic, nonflammable fluids.

Examine the appropriate boiling mixture heat transfer and pressure drop correlations, using the results of the work above to determine the dominant properties. Knowing this will indicate which property to give most priority in trying to find a combination of fluids, whose mixture will yield properties that are required.

Investigate the feasibility of developing an expert system to work backwards to find the mixture that yields the phase equilibria and properties required.

Investigate liquid-liquid systems as an alternative to a boiling (liquid-vapor) system.

Investigate the Catalytic Converter Technology.

The investigation of new technologies to replace or modify the existing catalytic converter is recommended. New concepts which would eliminate the high temperature thermal stability constraint on candidate heat transport fluids are needed. If the constraint were eliminated, some common refrigerants would be viable candidates for the manned-spacecraft thermal bus application. Examples (see Tables 1-8) are difluoromethane(IDN 485), chlorodifluoromethane(IDN 369), and dichlorodifluoromethane(IDN 431). Possible new concepts would include for example, low temperature operation and/or selective absorption.

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TABLES

Table 1. Top-ranked fluids for Temperature Range 1, Tbulk = 200 K

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
58	C3H6	PROPENE	1.000	0.494	0.778	0.991	0.836	0.988	2.121
57	C3H8	PROPANE	0.951	0.567	0.725	0.991	0.754	0.996	2.072
375	COS	CARBONYL SULPHIDE	1.000	0.494	0.812	0.833	0.967	0.187	2.034
9	C4H8	BUT-1-ENE	0.770	0.903	0.478	0.991	0.754	0.952	1.957
485	CH2F2	DIFLUOROMETHANE(32)	0.951	0.494	0.800	0.797	0.820	0.171	1.938
369	CHCLF2	CHLORODIFLUOROMETHAN	0.902	0.603	0.704	0.903	0.705	0.127	1.909
8	C4H10	BUTANE	0.754	0.964	0.454	0.797	0.623	0.984	1.880
49	C4H8	2-METHYLPROPENE	0.754	0.903	0.482	0.833	0.623	0.952	1.868
431	CCL2F2	DICHLORODIFLUOROMETH	0.885	0.697	0.637	0.948	0.344	0.088	1.851
48	C4H10	ISOBUTANE	0.754	0.845	0.516	0.961	0.344	0.984	1.839
60	C3H4	PROPYNE	0.836	0.752	0.563	0.367	0.902	0.873	1.815
163	H2S	HYDROGEN SULPHIDE	0.984	0.364	0.899	0.064	0.984	0.343	1.775
355	CH3CL	CHLOROMETHANE(40)	0.836	0.752	0.580	0.276	0.967	0.203	1.740
154	CL2	CHLORINE	0.869	0.639	0.664	0.367	0.836	0.084	1.740
216	C3H9N	TRIMETHYLAMINE	0.689	0.964	0.438	0.573	0.623	0.873	1.729
130	C2H3CL	VINYL CHLORIDE	0.689	0.803	0.516	0.942	0.623	0.211	1.725
492	C2H4F2	1,1-DIFLUOROETHANE(1	0.803	0.752	0.571	0.573	0.623	0.203	1.724
436	C2CLF5	CHLOROPENTAFLUOROETH	0.885	0.603	0.700	0.276	0.820	0.084	1.722
70	NH3	AMMONIA	0.836	0.639	0.613	0.015	1.000	0.873	1.693
490	C2H3CLF2	1-CHLORO-1,1-DIFLUOR	0.754	0.845	0.494	0.742	0.393	0.159	1.692
432	CBRCLF2	BROMOCHLORODIFLUOROM	0.689	0.903	0.468	0.961	0.262	0.040	1.672
7	C4H6	BUTA-1,3-DIENE	0.590	0.903	0.468	0.903	0.393	0.920	1.671
472	HBR	HYDROGEN BROMIDE	0.967	0.270	0.943	0.064	0.705	0.036	1.643
467	BCL3	BORON TRICHLORIDE	0.689	1.000	0.397	0.488	0.623	0.120	1.630
649	C2H3BR	VINYL BROMIDE	0.590	1.000	0.397	0.797	0.623	0.072	1.620
517	C4H8O	ETHYL VINYL ETHER	0.590	0.964	0.319	0.573	0.967	0.550	1.620
177	C2H5CL	CHLOROETHANE(160)	0.525	1.000	0.397	0.797	0.754	0.235	1.597
311	C5H10	PENT-1-ENE	0.459	0.991	0.338	0.979	0.623	0.873	1.595
486	CH3BR	BROMOMETHANE	0.689	0.964	0.424	0.197	0.820	0.052	1.568
313	C5H10	3-METHYLBUT-1-ENE	0.475	1.000	0.378	0.979	0.262	0.920	1.565
434	CHCL2F	DICHLOROFLUOROMETHAN	0.525	0.991	0.405	0.797	0.623	0.100	1.556
64	C2H4O	ACETALDEHYDE	0.459	1.000	0.352	0.694	0.967	0.494	1.551
193	C2H4O	ETHYLENE OXIDE(EPOXY	0.508	0.991	0.385	0.533	0.967	0.279	1.539
42	C5H12	ISOPENTANE	0.459	0.991	0.352	0.961	0.279	0.952	1.534
578	C4H12SI	TETRAMETHYLSILANE	0.590	0.991	0.352	0.367	0.557	0.813	1.529
554	CH5N	METHYLAMINE	0.557	0.903	0.431	0.197	0.967	0.769	1.511
228	SO2	SULPHUR DIOXIDE	0.689	0.845	0.458	0.015	0.967	0.088	1.501
109	C5H8	2-METHYLBUTA-1,3-DIE	0.361	0.991	0.319	0.903	0.623	0.920	1.471
374	C2H6S	ETHYL MERCAPTAN (ETH	0.344	0.964	0.319	0.918	0.754	0.343	1.414
312	C5H10	2-METHYLBUT-1-ENE	0.344	0.991	0.338	0.797	0.393	0.813	1.374
56	C5H12	PENTANE	0.361	0.964	0.319	0.742	0.393	0.920	1.363
435	C2CL2F4	1,2-DICHLORO-1,1,2,2	0.475	0.964	0.431	0.197	0.820	0.100	1.363
483	CBR2F2	DIBROMODIFLUOROMETHA	0.426	1.000	0.364	0.833	0.148	0.024	1.354
97	C4H10O	DIETHYL ETHER	0.344	0.964	0.319	0.573	0.623	0.649	1.315
423	C2H7N	DIMETHYLAMINE	0.361	0.991	0.378	0.197	0.623	0.769	1.268
440	CCL3F	TRICHLOROFLUOROMETHA	0.344	0.991	0.364	0.533	0.213	0.080	1.196
396	HF	HYDROGEN FLUORIDE	0.459	1.000	0.397	0.064	0.148	0.195	1.186
373	CH4S	METHANETHIOL	0.213	0.991	0.418	0.694	0.262	0.279	1.164
570	C2H6S	DIMETHYLSULPHIDE	0.295	0.964	0.288	0.276	0.705	0.343	1.150
365	CS2	CARBON DISULPHIDE	0.213	0.903	0.288	0.533	0.836	0.151	1.122

Table 2. Top-ranked fluids for Temperature Range 1, Tbulk = 250 K

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
9	C4H8	BUT-1-ENE	0.915	0.903	0.885	0.991	0.825	0.976	2.281
7	C4H6	BUTA-1,3-DIENE	0.894	0.903	0.870	0.903	0.841	0.928	2.225
48	C4H10	ISOBUTANE	0.915	0.845	0.927	0.961	0.619	0.984	2.219
49	C4H8	2-METHYLPROPENE	0.905	0.903	0.891	0.833	0.788	0.976	2.218
8	C4H10	BUTANE	0.894	0.964	0.845	0.797	0.767	0.976	2.204
130	C2H3CL	VINYL CHLORIDE	0.915	0.803	0.942	0.942	0.878	0.223	2.174
57	C3H8	PROPANE	0.984	0.567	0.873	0.991	0.767	0.996	2.167
12	C4H6	1-BUTYNE	0.857	0.991	0.764	0.718	0.947	0.853	2.148
58	C3H6	PROPENE	0.995	0.494	0.838	0.991	0.841	0.992	2.141
6	C4H6	1,2-BUTADIENE	0.831	0.991	0.748	0.797	0.841	0.853	2.118
60	C3H4	PROPYNE	0.947	0.752	1.000	0.367	0.942	0.928	2.114
216	C3H9N	TRIMETHYLAMINE	0.884	0.964	0.822	0.573	0.767	0.896	2.109
313	C5H10	3-METHYLBUT-1-ENE	0.815	1.000	0.700	0.979	0.598	0.928	2.101
373	CH4S	METHANETHIOL	0.852	0.991	0.786	0.694	0.984	0.291	2.096
431	CCL2F2	DICHLORODIFLUOROMETH	0.963	0.697	0.965	0.948	0.429	0.084	2.076
492	C2H4F2	1,1-DIFLUOROETHANE(1	0.947	0.752	0.995	0.573	0.767	0.203	2.066
143	CH2O	FORMALDEHYDE	0.963	0.803	0.976	0.197	0.995	0.522	2.065
369	CHCLF2	CHLORODIFLUOROMETHAN	0.979	0.603	0.873	0.903	0.741	0.112	2.060
432	CBRCLF2	BROMOCHLORODIFLUOROM	0.884	0.903	0.870	0.961	0.429	0.012	2.058
311	C5H10	PENT-1-ENE	0.767	0.991	0.637	0.979	0.767	0.896	2.054
177	C2H5CL	CHLOROETHANE(160)	0.815	1.000	0.736	0.797	0.878	0.251	2.049
434	CHCL2F	DICHLOROFLUOROMETHAN	0.831	0.991	0.756	0.797	0.767	0.084	2.029
649	C2H3BR	VINYL BROMIDE	0.836	1.000	0.725	0.797	0.767	0.056	2.024
375	COS	CARBONYL SULPHIDE	1.000	0.494	0.835	0.833	0.878	0.175	2.024
355	CH3CL	CHLOROMETHANE(40)	0.947	0.752	1.000	0.276	0.958	0.203	2.017
109	C5H8	2-METHYLBUTA-1,3-DIE	0.751	0.991	0.613	0.903	0.825	0.896	2.017
42	C5H12	ISOPENTANE	0.751	0.991	0.654	0.961	0.619	0.928	2.013
554	CH5N	METHYLAMINE	0.873	0.903	0.865	0.197	0.989	0.793	2.007
64	C2H4O	ACETALDEHYDE	0.772	1.000	0.678	0.694	0.968	0.490	1.995
193	C2H4O	ETHYLENE OXIDE(EPOXY	0.815	0.991	0.740	0.533	0.984	0.291	1.992
490	C2H3CLF2	1-CHLORO-1,1-DIFLUOR	0.884	0.845	0.905	0.742	0.429	0.151	1.992
170	C4H4	VINYL ACETYLENE	0.815	0.991	0.790	0.367	0.767	0.761	1.966
312	C5H10	2-METHYLBUT-1-ENE	0.746	0.991	0.627	0.797	0.741	0.853	1.965
70	NH3	AMMONIA	0.968	0.639	0.923	0.015	1.000	0.928	1.955
196	C2H2O	KETENE	0.931	0.494	0.824	0.770	0.921	0.291	1.952
423	C2H7N	DIMETHYLAMINE	0.825	0.991	0.753	0.197	0.926	0.853	1.952
485	CH2F2	DIFLUOROMETHANE(32)	0.963	0.494	0.795	0.797	0.825	0.171	1.949
517	C4H8O	ETHYL VINYL ETHER	0.799	0.964	0.580	0.573	0.942	0.590	1.932
467	BCL3	BORON TRICHLORIDE	0.852	1.000	0.740	0.488	0.630	0.096	1.930
211	C3H5CL	2-CHLOROPROPENE	0.746	1.000	0.678	0.797	0.741	0.251	1.930
374	C2H6S	ETHYL MERCAPTAN (ETH	0.704	0.964	0.594	0.918	0.921	0.378	1.920
154	CL2	CHLORINE	0.931	0.639	0.931	0.367	0.868	0.064	1.913
486	CH3BR	BROMOMETHANE	0.857	0.964	0.817	0.197	0.921	0.032	1.912
56	C5H12	PENTANE	0.741	0.964	0.597	0.742	0.661	0.928	1.909
578	C4H12SI	TETRAMETHYLSILANE	0.825	0.991	0.656	0.367	0.598	0.853	1.898
439	C2H2CLF3	1-CHLORO-2,2,2-TRIFL	0.836	0.991	0.745	0.424	0.630	0.112	1.894
228	SO2	SULPHUR DIOXIDE	0.884	0.845	0.896	0.015	0.963	0.064	1.868
97	C4H10O	DIETHYL ETHER	0.741	0.964	0.594	0.573	0.810	0.689	1.863
483	CBR2F2	DIBROMODIFLUOROMETHA	0.746	1.000	0.682	0.833	0.392	0.000	1.847
117	C5H8	1,3-PENTADIENE(CIS)	0.698	0.903	0.544	0.833	0.767	0.761	1.847
444	COCL2	PHOSGENE	0.815	0.991	0.319	0.718	0.825	0.064	1.825

Table 3. Top-ranked fluids for Temperature Range 1, Tbulk = 300 K

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
9	C4H8	BUT-1-ENE	0.934	0.903	0.821	0.991	0.778	0.972	2.264
7	C4H6	BUTA-1,3-DIENE	0.938	0.903	0.827	0.903	0.872	0.948	2.261
6	C4H6	1,2-BUTADIENE	0.889	0.991	0.905	0.797	0.893	0.892	2.253
311	C5H10	PENT-1-ENE	0.815	0.991	0.991	0.979	0.778	0.892	2.245
313	C5H10	3-METHYLBUT-1-ENE	0.852	1.000	0.967	0.979	0.560	0.928	2.237
12	C4H6	1-BUTYNE	0.872	0.991	0.891	0.718	0.893	0.857	2.204
49	C4H8	2-METHYLPROPENE	0.922	0.903	0.817	0.833	0.753	0.972	2.198
109	C5H8	2-METHYLBUTA-1,3-DIE	0.794	0.991	0.967	0.903	0.798	0.892	2.196
42	C5H12	ISOPENTANE	0.794	0.991	1.000	0.961	0.613	0.948	2.195
8	C4H10	BUTANE	0.901	0.964	0.846	0.797	0.663	0.976	2.191
64	C2H4O	ACETALDEHYDE	0.827	1.000	0.972	0.694	0.988	0.574	2.179
177	C2H5CL	CHLOROETHANE(160)	0.852	1.000	0.917	0.797	0.893	0.267	2.163
48	C4H10	ISOBUTANE	0.938	0.845	0.786	0.961	0.498	0.988	2.162
312	C5H10	2-METHYLBUT-1-ENE	0.794	0.991	0.983	0.797	0.753	0.857	2.158
373	CH4S	METHANETHIOL	0.877	0.991	0.875	0.694	0.988	0.295	2.157
216	C3H9N	TRIMETHYLAMINE	0.901	0.964	0.857	0.573	0.778	0.928	2.146
374	C2H6S	ETHYL MERCAPTAN (ETH	0.770	0.964	0.960	0.918	0.934	0.434	2.141
130	C2H3CL	VINYL CHLORIDE	0.947	0.803	0.764	0.942	0.893	0.243	2.139
211	C3H5CL	2-CHLOROPROPENE	0.815	1.000	0.983	0.797	0.794	0.243	2.130
649	C2H3BR	VINYL BROMIDE	0.852	1.000	0.943	0.797	0.778	0.056	2.129
434	CHCL2F	DICHLOROFLUOROMETHAN	0.856	0.991	0.896	0.797	0.778	0.080	2.113
56	C5H12	PENTANE	0.774	0.964	0.950	0.742	0.753	0.928	2.102
193	C2H4O	ETHYLENE OXIDE(EPOXY	0.852	0.991	0.899	0.533	0.988	0.295	2.094
517	C4H8O	ETHYL VINYL ETHER	0.815	0.964	0.955	0.573	0.893	0.610	2.090
97	C4H10O	DIETHYL ETHER	0.794	0.964	0.960	0.573	0.794	0.733	2.064
423	C2H7N	DIMETHYLAMINE	0.885	0.991	0.873	0.197	0.938	0.857	2.062
117	C5H8	1,3-PENTADIENE(CIS)	0.761	0.903	0.899	0.833	0.794	0.781	2.060
432	CBRCLF2	BROMOCHLORODIFLUOROM	0.901	0.903	0.832	0.961	0.296	0.020	2.035
554	CH5N	METHYLAMINE	0.914	0.903	0.786	0.197	0.992	0.857	2.023
57	C3H8	PROPANE	0.988	0.567	0.638	0.991	0.498	0.992	2.022
170	C4H4	VINYL ACETYLENE	0.827	0.991	0.875	0.367	0.778	0.821	2.020
483	CBR2F2	DIBROMODIFLUOROMETHA	0.794	1.000	0.983	0.833	0.296	0.000	1.997
58	C3H6	PROPENE	0.996	0.494	0.613	0.991	0.560	0.992	1.996
467	BCL3	BORON TRICHLORIDE	0.856	1.000	0.923	0.488	0.560	0.096	1.993
60	C3H4	PROPYNE	0.955	0.752	0.705	0.367	0.872	0.948	1.992
493	C2H5BR	BROMOETHANE	0.761	0.964	0.938	0.633	0.844	0.056	1.983
143	CH2O	FORMALDEHYDE	0.971	0.803	0.713	0.197	0.996	0.661	1.982
422	C2H7N	ETHYLAMINE	0.823	1.000	0.942	0.015	0.959	0.821	1.978
382	C3H5CL	ALLYL CHLORIDE	0.728	0.903	0.899	0.770	0.893	0.227	1.972
578	C4H12SI	TETRAMETHYLSILANE	0.815	0.991	1.000	0.367	0.296	0.892	1.969
182	C2H2CL2	VINYLIDENE CHLORIDE	0.733	0.991	0.980	0.694	0.613	0.143	1.965
486	CH3BR	BROMOMETHANE	0.881	0.964	0.865	0.197	0.909	0.032	1.952
197	C2H4O2	METHYL FORMATE	0.765	0.991	0.976	0.276	0.959	0.191	1.945
116	C6H12	TRANS-4-METHYLPENT-2	0.728	0.803	0.817	0.833	0.778	0.821	1.944
492	C2H4F2	1,1-DIFLUOROETHANE(1	0.967	0.752	0.696	0.573	0.613	0.243	1.940
396	HF	HYDROGEN FLUORIDE	0.877	1.000	0.965	0.064	0.663	0.207	1.935
570	C2H6S	DIMETHYLSULPHIDE	0.765	0.964	0.943	0.276	0.938	0.343	1.929
827	C6H12	3,3-DIMETHYLBUT-1-EN	0.737	0.903	0.923	0.573	0.560	0.857	1.927
440	CCL3F	TRICHLOROFLUOROMETHA	0.770	0.991	0.991	0.533	0.498	0.056	1.927
431	CCL2F2	DICHLORODIFLUOROMETH	0.955	0.697	0.689	0.948	0.247	0.096	1.922
196	C2H2O	KETENE	0.971	0.494	0.597	0.770	0.938	0.470	1.922

Table 4. Top-ranked fluids for Temperature Range 1, Tbulk = 350 K

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
48	C4H10	ISOBUTANE	0.944	0.845	0.605	0.961	0.996	0.988	2.195
6	C4H6	1,2-BUTADIENE	0.908	0.991	0.680	0.797	0.829	0.920	2.173
7	C4H6	BUTA-1,3-DIENE	0.944	0.903	0.630	0.903	0.697	0.952	2.153
109	C5H8	2-METHYLBUTA-1,3-DIE	0.805	0.991	0.795	0.903	0.801	0.900	2.139
311	C5H10	PENT-1-ENE	0.837	0.991	0.764	0.979	0.578	0.900	2.137
313	C5H10	3-METHYLBUT-1-ENE	0.869	1.000	0.722	0.979	0.382	0.940	2.122
42	C5H12	ISOPENTANE	0.829	0.991	0.756	0.961	0.498	0.940	2.108
9	C4H8	BUT-1-ENE	0.936	0.903	0.625	0.991	0.382	0.968	2.108
64	C2H4O	ACETALDEHYDE	0.857	1.000	0.713	0.694	0.972	0.622	2.107
432	CBRCLF2	BROMOCHLORODIFLUOROM	0.908	0.903	0.633	0.961	0.996	0.028	2.103
12	C4H6	1-BUTYNE	0.845	0.991	0.676	0.718	0.829	0.900	2.082
374	C2H6S	ETHYL MERCAPTAN (ETH	0.781	0.964	0.790	0.918	0.920	0.414	2.080
177	C2H5CL	CHLOROETHANE(160)	0.869	1.000	0.689	0.797	0.801	0.275	2.071
373	CH4S	METHANETHIOL	0.876	0.991	0.656	0.694	0.952	0.375	2.071
312	C5H10	2-METHYLBUT-1-ENE	0.821	0.991	0.768	0.797	0.578	0.869	2.065
8	C4H10	BUTANE	0.920	0.964	0.646	0.797	0.299	0.968	2.056
56	C5H12	PENTANE	0.813	0.964	0.803	0.742	0.629	0.920	2.056
211	C3H5CL	2-CHLOROPROPENE	0.837	1.000	0.725	0.797	0.801	0.243	2.050
49	C4H8	2-METHYLPROPENE	0.936	0.903	0.625	0.833	0.299	0.968	2.044
117	C5H8	1,3-PENTADIENE(CIS)	0.765	0.903	0.845	0.833	0.761	0.801	2.037
517	C4H8O	ETHYL VINYL ETHER	0.829	0.964	0.795	0.573	0.841	0.653	2.034
193	C2H4O	ETHYLENE OXIDE(EPOXY	0.876	0.991	0.668	0.533	0.976	0.375	2.032
130	C2H3CL	VINYL CHLORIDE	0.952	0.803	0.594	0.942	0.649	0.275	2.031
216	C3H9N	TRIMETHYLAMINE	0.908	0.964	0.656	0.573	0.498	0.940	2.018
649	C2H3BR	VINYL BROMIDE	0.857	1.000	0.710	0.797	0.649	0.052	2.015
578	C4H12SI	TETRAMETHYLSILANE	0.813	0.991	0.761	0.367	0.996	0.920	2.014
97	C4H10O	DIETHYL ETHER	0.821	0.964	0.786	0.573	0.697	0.761	2.004
434	CHCL2F	DICHLOROFLUOROMETHAN	0.876	0.991	0.671	0.797	0.578	0.084	2.003
423	C2H7N	DIMETHYLAMINE	0.912	0.991	0.648	0.197	0.912	0.900	1.999
492	C2H4F2	1,1-DIFLUOROETHANE(1	0.976	0.752	0.538	0.573	0.996	0.514	1.989
116	C6H12	TRANS-4-METHYLPENT-2	0.745	0.803	0.910	0.833	0.697	0.841	1.984
439	C2H2CLF3	1-CHLORO-2,2,2-TRIFL	0.880	0.991	0.656	0.424	0.996	0.131	1.978
382	C3H5CL	ALLYL CHLORIDE	0.753	0.903	0.846	0.770	0.892	0.211	1.973
46	C6H14	ISOHEXANE	0.717	0.803	0.923	0.942	0.578	0.869	1.973
554	CH5N	METHYLAMINE	0.936	0.903	0.577	0.197	0.992	0.900	1.966
493	C2H5BR	BROMOETHANE	0.781	0.964	0.817	0.633	0.892	0.052	1.963
444	COCL2	PHOSGENE	0.884	0.991	0.568	0.718	0.649	0.072	1.960
490	C2H3CLF2	1-CHLORO-1,1-DIFLUOR	0.904	0.845	0.597	0.742	0.757	0.175	1.957
103	C6H12	HEX-1-ENE	0.713	0.803	0.942	0.833	0.649	0.841	1.955
57	C3H8	PROPANE	0.988	0.567	0.510	0.991	0.398	0.992	1.952
632	C6H12	2-METHYLPENT-1-ENE	0.713	0.803	0.931	0.797	0.649	0.801	1.936
422	C2H7N	ETHYLAMINE	0.880	1.000	0.684	0.015	0.944	0.841	1.932
827	C6H12	3,3-DIMETHYLBUT-1-EN	0.781	0.903	0.832	0.573	0.498	0.869	1.923
170	C4H4	VINYL ACETYLENE	0.845	0.991	0.671	0.367	0.578	0.841	1.918
518	C5H10O	ETHYL ALLYL ETHER	0.665	0.752	0.960	0.961	0.697	0.622	1.915
58	C3H6	PROPENE	1.000	0.494	0.499	0.991	0.359	0.992	1.915
397	C5H12O	ETHYL PROPYL ETHER	0.713	0.803	0.938	0.718	0.697	0.685	1.913
634	C6H12	2-ETHYLBUT-1-ENE	0.697	0.752	0.943	0.742	0.801	0.761	1.909
396	HF	HYDROGEN FLUORIDE	0.916	1.000	0.707	0.064	0.841	0.227	1.909
431	CCL2F2	DICHLORODIFLUOROMETH	0.964	0.697	0.541	0.948	0.398	0.131	1.906
182	C2H2CL2	VINYLIDENE CHLORIDE	0.765	0.991	0.770	0.694	0.578	0.131	1.905

Table 5. Top-ranked fluids for Temperature Range 2, Tbulk = 275 K

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
7	C4H6	BUTA-1,3-DIENE	0.951	0.942	0.971	0.950	0.909	0.964	2.373
9	C4H8	BUT-1-ENE	0.951	0.942	0.960	0.995	0.850	0.982	2.373
10	C4H8	2-BUTENE(CIS)	0.937	0.977	0.992	0.915	0.909	0.942	2.372
8	C4H10	BUTANE	0.941	0.977	0.992	0.897	0.775	0.984	2.349
6	C4H6	1,2-BUTADIENE	0.920	0.992	0.951	0.897	0.909	0.917	2.340
12	C4H6	1-BUTYNE	0.920	0.992	0.971	0.857	0.944	0.887	2.339
49	C4H8	2-METHYLPROPENE	0.941	0.942	0.955	0.915	0.799	0.982	2.327
11	C4H8	2-BUTENE(TRANS)	0.941	0.977	1.000	0.709	0.850	0.972	2.310
216	C3H9N	TRIMETHYLAMINE	0.932	0.977	1.000	0.783	0.799	0.942	2.310
48	C4H10	ISOBUTANE	0.951	0.912	0.926	0.979	0.623	0.994	2.295
373	CH4S	METHANETHIOL	0.918	0.992	0.982	0.845	0.986	0.338	2.291
111	C2H6O	METHYL ETHER	0.970	0.850	0.847	0.933	0.909	0.855	2.281
313	C5H10	3-METHYLBUT-1-ENE	0.890	1.000	0.897	0.988	0.623	0.942	2.264
423	C2H7N	DIMETHYLAMINE	0.920	0.992	0.973	0.595	0.948	0.887	2.262
109	C5H8	2-METHYLBUTA-1,3-DIENE (ISOP	0.890	0.992	0.816	0.950	0.850	0.942	2.262
130	C2H3CL	VINYL CHLORIDE	0.951	0.882	0.912	0.970	0.909	0.286	2.258
554	CH5N	METHYLAMINE	0.937	0.942	0.951	0.595	0.988	0.887	2.253
177	C2H5CL	CHLOROETHANE(160)	0.890	1.000	0.942	0.897	0.909	0.316	2.249
66	C3H4	ALLENE	0.977	0.786	0.800	0.897	0.946	0.982	2.246
64	C2H4O	ACETALDEHYDE	0.874	1.000	0.888	0.845	0.986	0.583	2.238
311	C5H10	PENT-1-ENE	0.857	0.992	0.838	0.988	0.799	0.917	2.236
170	C4H4	VINYL ACETYLENE	0.888	0.992	0.982	0.680	0.850	0.855	2.236
193	C2H4O	ETHYLENE OXIDE(EPOXYETHANE)	0.890	0.992	0.951	0.763	0.986	0.338	2.227
60	C3H4	PROPYNE	0.972	0.850	0.852	0.680	0.927	0.964	2.223
42	C5H12	ISOPENTANE	0.855	1.000	0.852	0.979	0.674	0.964	2.220
649	C2H3BR	VINYL BROMIDE	0.902	1.000	0.926	0.897	0.850	0.068	2.218
434	CHCL2F	DICHLOROFLUOROMETHANE(21)	0.895	0.992	0.961	0.897	0.799	0.109	2.215
143	CH2O	FORMALDEHYDE	0.972	0.882	0.874	0.595	0.993	0.638	2.203
120	C5H10	2-PENTENE(CIS)	0.845	0.977	0.791	0.965	0.850	0.917	2.202
312	C5H10	2-METHYLBUT-1-ENE	0.848	0.992	0.831	0.897	0.799	0.917	2.197
121	C5H10	2-PENTENE(TRANS)	0.848	0.977	0.796	0.915	0.850	0.917	2.191
97	C4H10O	DIETHYL ETHER	0.890	0.992	0.806	0.783	0.850	0.773	2.191
57	C3H8	PROPANE	0.986	0.715	0.753	0.995	0.719	0.998	2.187
486	CH3BR	BROMOMETHANE	0.920	0.977	0.995	0.595	0.944	0.046	2.179
58	C3H6	PROPENE	0.995	0.671	0.724	0.995	0.799	0.996	2.178
432	CBRCLF2	BROMOCHLORODIFLUOROMETHANE(1	0.932	0.942	0.973	0.979	0.419	0.026	2.172
517	C4H8O	ETHYL VINYL ETHER	0.869	0.992	0.796	0.783	0.946	0.638	2.171
56	C5H12	PENTANE	0.845	0.977	0.800	0.869	0.775	0.964	2.166
211	C3H5CL	2-CHLOROPROPENE	0.852	1.000	0.878	0.897	0.799	0.316	2.164
374	C2H6S	ETHYL MERCAPTAN (ETHANETHIOL	0.827	0.992	0.806	0.958	0.944	0.425	2.164
110	C5H10	2-METHYL-2-BUTENE	0.838	0.977	0.779	0.883	0.850	0.887	2.162
492	C2H4F2	1,1-DIFLUOROETHANE(152A)	0.970	0.850	0.842	0.783	0.799	0.286	2.155
467	BCL3	BORON TRICHLORIDE	0.918	1.000	0.939	0.741	0.623	0.129	2.153
422	C2H7N	ETHYLAMINE	0.855	1.000	0.904	0.487	0.956	0.855	2.139
355	CH3CL	CHLOROMETHANE(40)	0.956	0.850	0.852	0.634	0.965	0.268	2.131
578	C4H12SI	TETRAMETHYLSILANE	0.874	1.000	0.858	0.680	0.576	0.917	2.127
117	C5H8	1,3-PENTADIENE(CIS)	0.822	0.942	0.739	0.915	0.850	0.809	2.114
490	C2H3CLF2	1-CHLORO-1,1-DIFLUOROETHANE(	0.923	0.912	0.927	0.869	0.419	0.181	2.112
228	SO2	SULPHUR DIOXIDE	0.941	0.912	0.926	0.445	0.977	0.109	2.108
70	NH3	AMMONIA	0.972	0.786	0.771	0.445	1.000	0.964	2.103

Table 6. Top-ranked fluids for Temperature Range 2, Tbulk = 290 K

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
6	C4H6	1,2-BUTADIENE	0.929	0.992	0.973	0.897	0.912	0.920	2.358
10	C4H8	2-BUTENE(CIS)	0.946	0.977	0.927	0.915	0.871	0.964	2.351
7	C4H6	BUTA-1,3-DIENE	0.959	0.942	0.888	0.950	0.912	0.964	2.349
9	C4H8	BUT-1-ENE	0.957	0.942	0.878	0.995	0.826	0.980	2.341
12	C4H6	1-BUTYNE	0.921	0.992	0.955	0.857	0.925	0.893	2.330
8	C4H10	BUTANE	0.948	0.977	0.909	0.897	0.773	0.984	2.323
109	C5H8	2-METHYLBUTA-1,3-DIENE (ISOP	0.906	0.992	0.904	0.950	0.852	0.940	2.313
313	C5H10	3-METHYLBUT-1-ENE	0.906	1.000	0.989	0.988	0.605	0.940	2.313
49	C4H8	2-METHYLPROPENE	0.953	0.942	0.877	0.915	0.807	0.980	2.309
311	C5H10	PENT-1-ENE	0.878	0.992	0.927	0.988	0.807	0.920	2.295
64	C2H4O	ACETALDEHYDE	0.882	1.000	0.982	0.845	0.983	0.606	2.285
177	C2H5CL	CHLOROETHANE(160)	0.906	1.000	0.980	0.897	0.912	0.324	2.281
11	C4H8	2-BUTENE(TRANS)	0.946	0.977	0.916	0.709	0.850	0.970	2.281
216	C3H9N	TRIMETHYLAMINE	0.929	0.977	0.926	0.783	0.807	0.940	2.279
373	CH4S	METHANETHIOL	0.921	0.992	0.942	0.845	0.983	0.342	2.278
48	C4H10	ISOBUTANE	0.959	0.912	0.852	0.979	0.605	0.994	2.270
423	C2H7N	DIMETHYLAMINE	0.929	0.992	0.942	0.595	0.951	0.920	2.263
42	C5H12	ISOPENTANE	0.865	1.000	0.942	0.979	0.652	0.964	2.262
120	C5H10	2-PENTENE(CIS)	0.861	0.977	0.892	0.965	0.852	0.920	2.258
111	C2H6O	METHYL ETHER	0.974	0.850	0.767	0.933	0.912	0.893	2.258
312	C5H10	2-METHYLBUT-1-ENE	0.865	0.992	0.923	0.897	0.807	0.920	2.253
193	C2H4O	ETHYLENE OXIDE(EPOXYETHANE)	0.906	0.992	0.971	0.763	0.985	0.342	2.250
97	C4H10O	DIETHYL ETHER	0.906	0.992	0.899	0.783	0.850	0.785	2.245
121	C5H10	2-PENTENE(TRANS)	0.861	0.977	0.894	0.915	0.850	0.920	2.243
649	C2H3BR	VINYL BROMIDE	0.906	1.000	0.995	0.897	0.807	0.072	2.241
130	C2H3CL	VINYL CHLORIDE	0.961	0.882	0.838	0.970	0.912	0.296	2.240
170	C4H4	VINYL ACETYLENE	0.897	0.992	0.942	0.680	0.850	0.861	2.230
554	CH5N	METHYLAMINE	0.948	0.942	0.861	0.595	0.989	0.893	2.230
434	CHCL2F	DICHLOROFLUOROMETHANE(21)	0.906	0.992	0.961	0.897	0.807	0.111	2.228
211	C3H5CL	2-CHLOROPROPENE	0.865	1.000	0.973	0.897	0.850	0.324	2.225
110	C5H10	2-METHYL-2-BUTENE	0.858	0.977	0.878	0.883	0.852	0.893	2.223
374	C2H6S	ETHYL MERCAPTAN (ETHANETHIOL	0.843	0.992	0.899	0.958	0.951	0.443	2.221
56	C5H12	PENTANE	0.861	0.977	0.897	0.869	0.773	0.964	2.220
517	C4H8O	ETHYL VINYL ETHER	0.878	0.992	0.897	0.783	0.925	0.640	2.216
66	C3H4	ALLENE	0.981	0.786	0.721	0.897	0.925	0.980	2.214
422	C2H7N	ETHYLAMINE	0.882	1.000	1.000	0.487	0.966	0.861	2.207
143	CH2O	FORMALDEHYDE	0.974	0.882	0.791	0.595	0.994	0.688	2.178
117	C5H8	1,3-PENTADIENE(CIS)	0.839	0.942	0.847	0.915	0.850	0.817	2.175
467	BCL3	BORON TRICHLORIDE	0.916	1.000	0.982	0.741	0.605	0.129	2.165
486	CH3BR	BROMOMETHANE	0.927	0.977	0.926	0.595	0.942	0.046	2.158
60	C3H4	PROPYNE	0.931	0.850	0.775	0.680	0.912	0.964	2.149
167	C3H6O	PROPYLENE OXIDE(1,2-EPOXYPRO	0.839	0.992	0.894	0.763	0.912	0.443	2.149
578	C4H12SI	TETRAMETHYLSILANE	0.878	1.000	0.948	0.680	0.457	0.920	2.144
432	CBRCLF2	BROMOCHLORODIFLUOROMETHANE(1	0.938	0.942	0.892	0.979	0.391	0.026	2.140
57	C3H8	PROPANE	0.987	0.715	0.689	0.995	0.605	0.996	2.139
556	C3H9N	ISOPROPYLAMINE	0.835	0.992	0.912	0.595	0.807	0.861	2.121
827	C6H12	3,3-DIMETHYLBUT-1-ENE	0.835	0.977	0.870	0.783	0.605	0.920	2.119
58	C3H6	PROPENE	0.994	0.671	0.653	0.995	0.652	0.996	2.119
483	CBR2F2	DIBROMODIFLUOROMETHANE(12B2)	0.861	1.000	0.973	0.915	0.457	0.008	2.116
826	C6H12	2,3-DIMETHYLBUT-1-ENE	0.811	0.912	0.783	0.973	0.773	0.861	2.113
197	C2H4O2	METHYL FORMATE	0.843	0.992	0.912	0.634	0.968	0.235	2.111

Table 7. Top-ranked fluids for Temperature Range 2, Tbulk = 305 K

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
109	C5H8	2-METHYLBUTA-1,3-DIENE (ISOP	0.893	0.992	0.992	0.950	0.842	0.936	2.333
6	C4H6	1,2-BUTADIENE	0.934	0.992	0.894	0.897	0.912	0.920	2.332
311	C5H10	PENT-1-ENE	0.885	0.992	0.995	0.988	0.797	0.936	2.329
7	C4H6	BUTA-1,3-DIENE	0.961	0.942	0.819	0.950	0.904	0.962	2.322
10	C4H8	2-BUTENE(CIS)	0.943	0.977	0.861	0.915	0.842	0.962	2.315
9	C4H8	BUT-1-ENE	0.961	0.942	0.813	0.995	0.760	0.978	2.306
120	C5H10	2-PENTENE(CIS)	0.865	0.977	0.980	0.965	0.842	0.920	2.295
313	C5H10	3-METHYLBUT-1-ENE	0.908	1.000	0.942	0.988	0.588	0.962	2.295
12	C4H6	1-BUTYNE	0.916	0.992	0.877	0.857	0.912	0.920	2.295
42	C5H12	ISOPENTANE	0.879	1.000	0.985	0.979	0.627	0.962	2.288
64	C2H4O	ACETALDEHYDE	0.900	1.000	0.942	0.845	0.980	0.616	2.287
121	C5H10	2-PENTENE(TRANS)	0.865	0.977	0.982	0.915	0.842	0.920	2.281
312	C5H10	2-METHYLBUT-1-ENE	0.865	0.992	1.000	0.897	0.760	0.920	2.274
97	C4H10O	DIETHYL ETHER	0.893	0.992	0.989	0.783	0.842	0.791	2.268
8	C4H10	BUTANE	0.947	0.977	0.838	0.897	0.635	0.984	2.265
374	C2H6S	ETHYL MERCAPTAN (ETHANETHIOL	0.850	0.992	0.989	0.958	0.943	0.469	2.265
110	C5H10	2-METHYL-2-BUTENE	0.865	0.977	0.971	0.883	0.842	0.895	2.264
49	C4H8	2-METHYLPROPENE	0.955	0.942	0.810	0.915	0.686	0.978	2.260
373	CH4S	METHANETHIOL	0.928	0.992	0.867	0.845	0.977	0.388	2.259
517	C4H8O	ETHYL VINYL ETHER	0.885	0.992	0.985	0.783	0.912	0.646	2.257
56	C5H12	PENTANE	0.865	0.977	0.982	0.869	0.760	0.962	2.255
177	C2H5CL	CHLOROETHANE(160)	0.908	1.000	0.899	0.897	0.904	0.322	2.249
11	C4H8	2-BUTENE(TRANS)	0.947	0.977	0.842	0.709	0.797	0.968	2.241
423	C2H7N	DIMETHYLAMINE	0.934	0.992	0.865	0.595	0.947	0.920	2.236
211	C3H5CL	2-CHLOROPROPENE	0.879	1.000	0.960	0.897	0.842	0.322	2.233
48	C4H10	ISOBUTANE	0.961	0.912	0.783	0.979	0.543	0.994	2.232
193	C2H4O	ETHYLENE OXIDE(EPOXYETHANE)	0.914	0.992	0.888	0.763	0.982	0.352	2.226
649	C2H3BR	VINYL BROMIDE	0.914	1.000	0.918	0.897	0.797	0.070	2.217
111	C2H6O	METHYL ETHER	0.973	0.850	0.700	0.933	0.842	0.895	2.216
117	C5H8	1,3-PENTADIENE(CIS)	0.842	0.942	0.939	0.915	0.842	0.831	2.215
130	C2H3CL	VINYL CHLORIDE	0.963	0.882	0.767	0.970	0.904	0.304	2.213
554	CH5N	METHYLAMINE	0.953	0.942	0.779	0.595	0.988	0.920	2.204
167	C3H6O	PROPYLENE OXIDE(1,2-EPOXYPRO	0.850	0.992	0.989	0.763	0.912	0.469	2.201
216	C3H9N	TRIMETHYLAMINE	0.879	0.977	0.858	0.783	0.797	0.936	2.199
434	CHCL2F	DICHLOROFLUOROMETHANE(21)	0.914	0.992	0.878	0.897	0.760	0.109	2.193
170	C4H4	VINYL ACETYLENE	0.900	0.992	0.867	0.680	0.797	0.863	2.192
422	C2H7N	ETHYLAMINE	0.900	1.000	0.912	0.487	0.965	0.863	2.190
66	C3H4	ALLENE	0.977	0.786	0.648	0.897	0.904	0.984	2.178
556	C3H9N	ISOPROPYLAMINE	0.846	0.992	1.000	0.595	0.797	0.863	2.167
827	C6H12	3,3-DIMETHYLBUT-1-ENE	0.842	0.977	0.960	0.783	0.588	0.920	2.159
826	C6H12	2,3-DIMETHYLBUT-1-ENE	0.822	0.912	0.877	0.973	0.760	0.863	2.159
197	C2H4O2	METHYL FORMATE	0.850	0.992	1.000	0.634	0.965	0.237	2.154
493	C2H5BR	BROMOETHANE	0.842	0.977	0.971	0.813	0.904	0.083	2.152
570	C2H6S	DIMETHYLSULPHIDE	0.850	0.977	0.975	0.634	0.947	0.388	2.147
114	C6H12	4-METHYLPENT-1-ENE	0.828	0.912	0.888	0.970	0.635	0.895	2.147
382	C3H5CL	ALLYL CHLORIDE	0.828	0.942	0.931	0.883	0.912	0.270	2.146
143	CH2O	FORMALDEHYDE	0.973	0.882	0.710	0.595	0.992	0.702	2.145
115	C6H12	CIS-4-METHYLPENT-2-ENE	0.828	0.912	0.874	0.897	0.760	0.895	2.144
19	C5H8	CYCLOPENTENE	0.801	0.942	0.939	0.883	0.842	0.616	2.143
578	C4H12SI	TETRAMETHYLSILANE	0.879	1.000	0.982	0.680	0.357	0.920	2.139
633	C6H12	3-METHYLPENT-1-ENE	0.828	0.912	0.888	0.970	0.588	0.895	2.137

Table 8. Top-ranked fluids for Temperature Range 2, Tbulk = 320 K

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
6	C4H6	1,2-BUTADIENE	0.940	0.992	0.824	0.897	0.909	0.932	2.310
120	C5H10	2-PENTENE(CIS)	0.875	0.977	0.955	0.965	0.839	0.918	2.295
311	C5H10	PENT-1-ENE	0.887	0.992	0.918	0.988	0.750	0.932	2.290
7	C4H6	BUTA-1,3-DIENE	0.962	0.942	0.747	0.950	0.873	0.964	2.288
10	C4H8	2-BUTENE(CIS)	0.942	0.977	0.791	0.915	0.819	0.964	2.282
109	C5H8	2-METHYLBUTA-1,3-DIENE (ISOP	0.859	0.992	0.942	0.950	0.841	0.932	2.278
110	C5H10	2-METHYL-2-BUTENE	0.875	0.977	0.967	0.883	0.839	0.893	2.272
121	C5H10	2-PENTENE(TRANS)	0.875	0.977	0.951	0.915	0.791	0.918	2.268
12	C4H6	1-BUTYNE	0.917	0.992	0.810	0.857	0.909	0.918	2.268
313	C5H10	3-METHYLBUT-1-ENE	0.911	1.000	0.874	0.988	0.569	0.956	2.266
42	C5H12	ISOPENTANE	0.887	1.000	0.909	0.979	0.624	0.956	2.264
64	C2H4O	ACETALDEHYDE	0.901	1.000	0.870	0.845	0.978	0.626	2.260
374	C2H6S	ETHYL MERCAPTAN (ETHANETHIOL	0.859	0.992	0.942	0.958	0.944	0.483	2.256
312	C5H10	2-METHYLBUT-1-ENE	0.877	0.992	0.923	0.897	0.750	0.918	2.253
9	C4H8	BUT-1-ENE	0.958	0.942	0.739	0.995	0.634	0.976	2.248
517	C4H8O	ETHYL VINYL ETHER	0.887	0.992	0.948	0.783	0.909	0.664	2.245
8	C4H10	BUTANE	0.948	0.977	0.771	0.897	0.624	0.982	2.237
56	C5H12	PENTANE	0.875	0.977	0.951	0.869	0.666	0.956	2.234
117	C5H8	1,3-PENTADIENE(CIS)	0.849	0.942	0.992	0.915	0.791	0.837	2.233
373	CH4S	METHANETHIOL	0.924	0.992	0.796	0.845	0.976	0.402	2.228
177	C2H5CL	CHLOROETHANE(160)	0.911	1.000	0.831	0.897	0.879	0.326	2.220
49	C4H8	2-METHYLPROPENE	0.956	0.942	0.739	0.915	0.624	0.976	2.220
423	C2H7N	DIMETHYLAMINE	0.940	0.992	0.786	0.595	0.946	0.918	2.211
211	C3H5CL	2-CHLOROPROPENE	0.887	1.000	0.883	0.897	0.839	0.326	2.209
193	C2H4O	ETHYLENE OXIDE(EPOXYETHANE)	0.917	0.992	0.816	0.763	0.978	0.354	2.199
167	C3H6O	PROPYLENE OXIDE(1,2-EPOXYPRO	0.859	0.992	0.939	0.763	0.918	0.483	2.192
97	C4H10O	DIETHYL ETHER	0.841	0.992	0.939	0.783	0.819	0.795	2.191
11	C4H8	2-BUTENE(TRANS)	0.946	0.977	0.775	0.709	0.666	0.972	2.188
649	C2H3BR	VINYL BROMIDE	0.917	1.000	0.858	0.897	0.750	0.070	2.186
111	C2H6O	METHYL ETHER	0.976	0.850	0.632	0.933	0.791	0.918	2.184
115	C6H12	CIS-4-METHYLPENT-2-ENE	0.835	0.912	0.960	0.897	0.750	0.893	2.183
382	C3H5CL	ALLYL CHLORIDE	0.835	0.942	0.995	0.883	0.918	0.272	2.180
130	C2H3CL	VINYL CHLORIDE	0.964	0.882	0.704	0.970	0.841	0.326	2.178
826	C6H12	2,3-DIMETHYLBUT-1-ENE	0.825	0.912	0.961	0.973	0.666	0.869	2.177
554	CH5N	METHYLAMINE	0.956	0.942	0.706	0.595	0.984	0.918	2.177
422	C2H7N	ETHYLAMINE	0.917	1.000	0.838	0.487	0.958	0.869	2.176
116	C6H12	TRANS-4-METHYLPENT-2-ENE	0.833	0.882	0.942	0.915	0.791	0.893	2.173
114	C6H12	4-METHYLPENT-1-ENE	0.833	0.912	0.971	0.970	0.569	0.893	2.171
19	C5H8	CYCLOPENTENE	0.807	0.942	0.992	0.883	0.839	0.626	2.170
827	C6H12	3,3-DIMETHYLBUT-1-ENE	0.849	0.977	0.980	0.783	0.569	0.918	2.170
48	C4H10	ISOBUTANE	0.960	0.912	0.721	0.979	0.356	0.994	2.169
633	C6H12	3-METHYLPENT-1-ENE	0.825	0.912	0.971	0.970	0.569	0.893	2.163
493	C2H5BR	BROMOETHANE	0.855	0.977	0.961	0.813	0.909	0.083	2.162
170	C4H4	VINYL ACETYLENE	0.901	0.992	0.800	0.680	0.750	0.869	2.157
434	CHCL2F	DICHLOROFLUOROMETHANE(21)	0.917	0.992	0.813	0.897	0.666	0.119	2.152
383	C3H7CL	1-CHLOROPROPANE	0.825	0.942	1.000	0.845	0.841	0.326	2.151
118	C5H8	1,3-PENTADIENE(TRANS)	0.855	0.977	0.982	0.554	0.791	0.869	2.147
570	C2H6S	DIMETHYLSULPHIDE	0.855	0.977	0.960	0.634	0.946	0.402	2.147
556	C3H9N	ISOPROPYLAMINE	0.859	0.992	0.918	0.595	0.791	0.869	2.146
216	C3H9N	TRIMETHYLAMINE	0.873	0.977	0.786	0.783	0.666	0.956	2.140
445	C3H8O2	DIMETHOXYMETHANE	0.835	0.977	0.980	0.709	0.839	0.402	2.136

Table 9. Comparison of ranking factors for water and ammonia with those for the top-ranked fluids.

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
7	C4H6	BUTA-1,3-DIENE	0.951	0.942	0.971	0.950	0.909	0.964	2.37
70	NH3	AMMONIA	0.972	0.786	0.771	0.445	1.000	0.964	2.10
63	H2O	WATER	0.159	0.715	0.223	0.008	0.998	0.229	0.83

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
6	C4H6	1,2-BUTADIENE	0.929	0.992	0.973	0.897	0.912	0.920	2.36
70	NH3	AMMONIA	0.981	0.786	0.685	0.445	0.998	0.970	2.08
63	H2O	WATER	0.180	0.715	0.346	0.008	1.000	0.227	0.90

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
109	C5H8	2-METHYLBUTA-1,3-DIENE (ISOP	0.893	0.992	0.992	0.950	0.842	0.936	2.33
70	NH3	AMMONIA	0.982	0.786	0.602	0.445	0.996	0.968	2.04
63	H2O	WATER	0.279	0.715	0.501	0.008	1.000	0.227	1.06

IDN		SPECIES	WFFOMB	WFNBP	WFPVAP	WFTMP	WFLTF	WFDEN	TOTAL
6	C4H6	1,2-BUTADIENE	0.940	0.992	0.824	0.897	0.909	0.932	2.31
70	NH3	AMMONIA	0.982	0.786	0.524	0.445	0.996	0.972	2.01
63	H2O	WATER	0.374	0.715	0.648	0.008	1.000	0.225	1.22

Table 10. Product of reduced temperature and pressure for top and bottom ranked fluids in Temperature Range 2.
(Ranking on the basis of thermal performance-FOMB)

top ranked by FOMB

275 K

IDN	SPECIES		TRED*PRED
482	CBRF3	BROMOTRIFLUOROMETHANE(13B1)	0.1811
375	COS	CARBONYL SULPHIDE	0.0801
155	HCL	HYDROGEN CHLORIDE	0.2725
163	H2S	HYDROGEN SULPHIDE	0.0893
58	C3H6	PROPENE	0.1011
485	CH2F2	DIFLUOROMETHANE(32)	0.1160
57	C3H8	PROPANE	0.0876
369	CHCLF2	CHLORODIFLUOROMETHANE(22)	0.0790
436	C2CLF5	CHLOROPENTAFLUOROETHANE(115)	0.1165
472	HBR	HYDROGEN BROMIDE	0.1141
66	C3H4	ALLENE	0.0517
70	NH3	AMMONIA	0.0276
143	CH2O	FORMALDEHYDE	0.0235
60	C3H4	PROPYNE	0.0334
111	C2H6O	METHYL ETHER	0.0375
431	CCL2F2	DICHLORODIFLUOROMETHANE(12)	0.0568
492	C2H4F2	1,1-DIFLUOROETHANE(152A)	0.0460
196	C2H2O	KETENE	0.0932
355	CH3CL	CHLOROMETHANE(40)	0.0272
154	CL2	CHLORINE	0.0324
130	C2H3CL	VINYL CHLORIDE	0.0231
9	C4H8	BUT-1-ENE	0.0224
48	C4H10	ISOBUTANE	0.0309
7	C4H6	BUTA-1,3-DIENE	0.0192
49	C4H8	2-METHYLPROPENE	0.0233

Table 10 (continued)

bottom ranked by FOMB

275 K

IDN		SPECIES	TRED*PRED
607	C7H7CL	O-CHLOROTOLUENE	0.0000
680	C6H15N	N-HEXYLAMINE	0.0000
67	C3H6O	PROP-2-ENE-1-OL	0.0001
331	C7H14	CYCLOHEPTANE	0.0001
500	C9F20	PERFLURONONANE	0.0001
279	C9H20	2,2,3,3-TETRAMETHYLPENTANE	0.0000
506	C6H5BR	BROMOBENZENE	0.0000
711	C5H8O	CYCLOPENTANONE	0.0000
426	C5H11N	PIPERIDINE	0.0001
805	C4H5N	PYRROLE	0.0000
371	C4H6CL2	1,3-DICHLOROBUTENE-2(TRANS)	0.0000
859	C10H16	ALPHA-PINENE	0.0000
229	C3H8O2	ETHYLENE GLYCOL MONOMETHYL E	0.0000
389	C2H2CL4	1,1,2,2-TETRACHLOROETHANE	0.0000
706	C8H14	CYCLOOCTENE	0.0000
385	C3H5CL3	1-2-3 TRICHLOROPROPANE	0.0000
39	C3H8O	PROPAN-2-OL	0.0001
81	C6H10O	CYCLOHEXANONE	0.0000
731	C4H9NO	MORPHOLINE	0.0000
59	C3H8O	PROPAN-1-OL	0.0000
390	C2HCL5	PENTACHLOROETHANE(120)	0.0000
510	C10F18	PERFLURODECALIN	0.0001
172	C4H10O	BUTAN-2-OL(SECBUTANOL)	0.0000
171	C4H10O	2-METHYLPROPAN-1-OL(ISOBUTAN	0.0000
189	C6H14O	4-METHYL-2-PENTANOL	0.0000
714	C5H11N	CYCLOPENTYLAMINE	0.0001
512	C5H12O	2-METHYLBUTAN-2-OL	0.0001
424	C6H13N	CYCLOHEXYLAMINE	0.0000

Table 10. (continued)

top ranked by FOMB

290 K

IDN	SPECIES		TRED*PRED
482	CBRF3	BROMOTRIFLUOROMETHANE(13B1)	0.2842
375	COS	CARBONYL SULPHIDE	0.1310
485	CH2F2	DIFLUOROMETHANE(32)	0.1914
58	C3H6	PROPENE	0.1619
163	H2S	HYDROGEN SULPHIDE	0.1430
155	HCL	HYDROGEN CHLORIDE	0.4180
57	C3H8	PROPANE	0.1417
436	C2CLF5	CHLOROPENTAFLUOROETHANE(115)	0.1915
369	CHCLF2	CHLORODIFLUOROMETHANE(22)	0.1310
472	HBR	HYDROGEN BROMIDE	0.1777
70	NH3	AMMONIA	0.0490
66	C3H4	ALLENE	0.0885
143	CH2O	FORMALDEHYDE	0.0424
196	C2H2O	KETENE	0.1493
111	C2H6O	METHYL ETHER	0.0645
492	C2H4F2	1,1-DIFLUOROETHANE(152A)	0.0793
431	CCL2F2	DICHLORODIFLUOROMETHANE(12)	0.0947
355	CH3CL	CHLOROMETHANE(40)	0.0467
130	C2H3CL	VINYL CHLORIDE	0.0402
154	CL2	CHLORINE	0.0540
48	C4H10	ISOBUTANE	0.0533
7	C4H6	BUTA-1,3-DIENE	0.0342
9	C4H8	BUT-1-ENE	0.0396
49	C4H8	2-METHYLPROPENE	0.0409
554	CH5N	METHYLAMINE	0.0237
228	SO2	SULPHUR DIOXIDE	0.0254

Table 10 (continued)

bottom ranked by FOMB

290 K

IDN	SPECIES		TRED*PRED
229	C3H8O2	ETHYLENE GLYCOL MONOMETHYL E	0.0001
424	C6H13N	CYCLOHEXYLAMINE	0.0001
91	C6H12O3	2-ETHOXYETHYL ACETATE	0.0000
731	C4H9NO	MORPHOLINE	0.0001
505	C6H4CL2	1,2-DICHLOROBENZENE	0.0000
715	C7H7BR	O-BROMOTOLUENE	0.0000
213	C6H12O2	DIACETONE ALCOHOL	0.0000
367	C12H26	2,2,4,6,6-PENTAMETHYLHEPTANE	0.0000
363	C5H4O2	FURFURAL	0.0000
797	C9H10	INDANE	0.0000
385	C3H5CL3	1-2-3 TRICHLOROPROPANE	0.0000
81	C6H10O	CYCLOHEXANONE	0.0000
509	C6H5I	IODOBENZENE	0.0000
726	C5H10CL2	1,5-DICHLOROPENTANE	0.0000
390	C2HCL5	PENTACHLOROETHANE(120)	0.0000
510	C10F18	PERFLUORODECALIN	0.0003
172	C4H10O	BUTAN-2-OL(SECBUTANOL)	0.0002
512	C5H12O	2-METHYLBUTAN-2-OL	0.0002
793	C10H18	TRANS-DECALIN	0.0000
238	C5H9CL3	1,2,3-TRICHLORO-2-METHYLBUTA	0.0000
171	C4H10O	2-METHYLPROPAN-1-OL(ISOBUTAN	0.0001
189	C6H14O	4-METHYL-2-PENTANOL	0.0001
714	C5H11N	CYCLOPENTYLAMINE	0.0003
394	C5H12O	PENTAN-1-OL	0.0000

Table 10. (continued)

top ranked by FOMB

305 K

IDN	SPECIES		TRED*PRED
482	CBRF3	BROMOTRIFLUOROMETHANE(13B1)	0.4283
485	CH2F2	DIFLUOROMETHANE(32)	0.3014
375	COS	CARBONYL SULPHIDE	0.2059
58	C3H6	PROPENE	0.2478
163	H2S	HYDROGEN SULPHIDE	0.2182
155	HCL	HYDROGEN CHLORIDE	0.6196
436	C2CLF5	CHLOROPENTAFLUOROETHANE(115)	0.2998
57	C3H8	PROPANE	0.2188
369	CHCLF2	CHLORODIFLUOROMETHANE(22)	0.2066
472	HBR	HYDROGEN BROMIDE	0.2674
70	NH3	AMMONIA	0.0820
66	C3H4	ALLENE	0.1440
196	C2H2O	KETENE	0.2277
492	C2H4F2	1,1-DIFLUOROETHANE(152A)	0.1294
143	CH2O	FORMALDEHYDE	0.0723
111	C2H6O	METHYL ETHER	0.1047
431	CCL2F2	DICHLORODIFLUOROMETHANE(12)	0.1499
355	CH3CL	CHLOROMETHANE(40)	0.0759
130	C2H3CL	VINYL CHLORIDE	0.0658
7	C4H6	BUTA-1,3-DIENE	0.0573
154	CL2	CHLORINE	0.0857
48	C4H10	ISOBUTANE	0.0870
9	C4H8	BUT-1-ENE	0.0659
49	C4H8	2-METHYLPROPENE	0.0678
414	NO2	NITROGEN DIOXIDE	0.0115
554	CH5N	METHYLAMINE	0.0419
228	SO2	SULPHUR DIOXIDE	0.0445
8	C4H10	BUTANE	0.0566

Table 10 (continued)

bottom ranked by FOMB

305 K

IDN	SPECIES		TRED*PRED
385	C3H5CL3	1-2-3 TRICHLOROPROPANE	0.0001
510	C10F18	PERFLUORODECALIN	0.0007
509	C6H5I	IODOBENZENE	0.0000
620	C9H18O2	N-PENTYL N-BUTYRATE	0.0000
62	C11H24	UNDECANE	0.0000
665	C9H18O	METHYL N-HEPTYL KETONE	0.0000
789	C8H18S	OCTANE-1-THIOL	0.0000
171	C4H10O	2-METHYLPROPAN-1-OL(ISOBUTAN	0.0003
797	C9H10	INDANE	0.0000
615	C9H18O2	N-HEPTYL ACETATE	0.0000
420	C7H5OCL	BENZOYL CHLORIDE	0.0000
363	C5H4O2	FURFURAL	0.0000
582	C10H30O3SI4	DECAMETHYLTETRASILOXANE	0.0000
748	C9H18O2	N-OCTYL FORMATE	0.0000
793	C10H18	TRANS-DECALIN	0.0000
847	C6H10O4	DIETHYL OXALATE	0.0000
726	C5H10CL2	1,5-DICHLOROPENTANE	0.0000
189	C6H14O	4-METHYL-2-PENTANOL	0.0002
714	C5H11N	CYCLOPENTYLAMINE	0.0008
757	C10H20O2	N-PENTYL VALERATE	0.0000
238	C5H9CL3	1,2,3-TRICHLORO-2-METHYLBUTA	0.0000
394	C5H12O	PENTAN-1-OL	0.0001
364	C6H14O2	ETHYLENE GLYCOL MONO-N-BUTYL	0.0000
647	C2H3BR3	1,1,2-TRIBROMOETHANE	0.0000
415	C6H7N	ANILINE	0.0000
104	C6H14O	HEXAN-1-OL	0.0000
704	C10H20	CYCLODECANE	0.0000
588	C10H30O5SI5	DECAMETHYLCYCLOPENTASILOXANE	0.0001
142	C8H18O	2-ETHYLHEXANOL	0.0000

Table 10. (continued)

top ranked by FOMB

320 K

IDN	SPECIES		TRED*PRED
482	CBRF3	BROMOTRIFLUOROMETHANE(13B1)	0.6248
485	CH2F2	DIFLUOROMETHANE(32)	0.4567
58	C3H6	PROPENE	0.3657
375	COS	CARBONYL SULPHIDE	0.3090
436	C2CLF5	CHLOROPENTAFLUOROETHANE(115)	0.4510
163	H2S	HYDROGEN SULPHIDE	0.3196
57	C3H8	PROPANE	0.3254
155	HCL	HYDROGEN CHLORIDE	0.0660
369	CHCLF2	CHLORODIFLUOROMETHANE(22)	0.3127
472	HBR	HYDROGEN BROMIDE	0.3905
70	NH3	AMMONIA	0.1307
196	C2H2O	KETENE	0.3335
492	C2H4F2	1,1-DIFLUOROETHANE(152A)	0.2014
66	C3H4	ALLENE	0.2215
111	C2H6O	METHYL ETHER	0.1623
431	CCL2F2	DICHLORODIFLUOROMETHANE(12)	0.2275
143	CH2O	FORMALDEHYDE	0.1171
355	CH3CL	CHLOROMETHANE(40)	0.1177
130	C2H3CL	VINYL CHLORIDE	0.1028
414	NO2	NITROGEN DIOXIDE	0.0226
7	C4H6	BUTA-1,3-DIENE	0.0911
48	C4H10	ISOBUTANE	0.1355
154	CL2	CHLORINE	0.1301
9	C4H8	BUT-1-ENE	0.1044
49	C4H8	2-METHYLPROPENE	0.1066

Table 10 (continued)

bottom ranked by FOMB

320 K

IDN	SPECIES		TRED*PRED
89	C12H24	DODEC-1-ENE	0.0000
789	C8H18S	OCTANE-1-THIOL	0.0001
700	C8H18O3	DIETHYLENE GLYCOL DIETHYL ET	0.0000
394	C5H12O	PENTAN-1-OL	0.0002
728	C9H13N	N,N-DIMETHYL-P-TOLUIDINE	0.0000
28	C12H26	DODECANE	0.0000
748	C9H18O2	N-OCTYL FORMATE	0.0000
566	C8H7N	P-TOLUNITRILE	0.0000
751	C11H22O2	N-OCTYL PROPIONATE	0.0000
757	C10H20O2	N-PENTYL VALERATE	0.0001
141	TOH20O2	2-ETHYLHEXYL ACRYLATE	0.0000
419	C10H15N	N,N-DIETHYLANILINE	0.0000
647	C2H3BR3	1,1,2-TRIBROMOETHANE	0.0000
364	C6H14O2	ETHYLENE GLYCOL MONO-N-BUTYL	0.0000
104	C6H14O	HEXAN-1-OL	0.0001
704	C10H20	CYCLODECANE	0.0000
415	C6H7N	ANILINE	0.0000
696	C5H12O3	DIETHYLENE GLYCOL MONOMETHYL	0.0000
588	C10H30O5SI5	DECAMETHYLCYCLOPENTASILOXANE	0.0001
392	C4CL6	HEXACHLOROBUTADIENE	0.0000
513	C8H18O	OCTAN-2-OL	0.0000
142	C8H18O	2-ETHYLHEXANOL	0.0001
4	ALPHANOL	ALPHANOL	0.0000
829	C10H20O	DECANAL	0.0000
405	C3H6OCL2	2-3-DICHLOROPROPANOL	0.0000

Table 11. Summary of responses from commercial suppliers of heat transfer fluids.

COMPANY	FLUID	FLUID DESCRIPTION
3M	FC72	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC84	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC77	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC104	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC75	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC40	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC43	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC5311	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC70	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC5312	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC71	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
3M	FC87	COMPLETELY FLUORINATED ORGANIC COMPOUNDS
AKZO CHEMICALS	DEMEON 13/87	AZEOTROPE (13W%DIMETHYLETHER,87W%R12)
AUSIMONT	GALDEN D/80	PERFLUORINATED LIQUID
AUSIMONT	GALDEN D02	PERFLUORINATED LIQUID
AUSIMONT	GALDEN D03	PERFLUORINATED LIQUID
AUSIMONT	GALDEN D05	PERFLUORINATED LIQUID
AUSIMONT	GALDEN D10	PERFLUORINATED LIQUID
AUSIMONT	GALDEN D20	PERFLUORINATED LIQUID
AUSIMONT	GALDEN D40	PERFLUORINATED LIQUID
AUSIMONT	LS/215	PERFLUORINATED LIQUID
AUSIMONT	LS/230	PERFLUORINATED LIQUID
AUSIMONT	HS/260	PERFLUORINATED LIQUID
DOW CORNING	SYLTHERM 800	MODIFIED DIMETHYLSILOXANE
DOW CORNING	SYLTHERM XLT	DIMETHYLSILOXANE POLYMER
DOW CORNING	DC200	DIMETHYL,PHENYLMETHYL,AND TRIFLUOROPROPYL SILICONE FLUID
DOW CORNING	DC510	DIMETHYL,PHENYLMETHYL,AND TRIFLUOROPROPYL SILICONE FLUID
DOW CORNING	DC550	DIMETHYL,PHENYLMETHYL,AND TRIFLUOROPROPYL SILICONE FLUID
DOW CORNING	DC710	DIMETHYL,PHENYLMETHYL,AND TRIFLUOROPROPYL SILICONE FLUID
DOW CORNING	DCFS1265	DIMETHYL,PHENYLMETHYL,AND TRIFLUOROPROPYL SILICONE FLUID
GENERAL ELECTRIC	SF97-50	POLYDIMETHYLSILOXANE
GENERAL ELECTRIC	SF96-100	POLYDIMETHYLSILOXANE
GENERAL ELECTRIC	SF1154	COPOLYMER CONTAINING BOTH METHY AND PHENYL UNITS
GENERAL ELECTRIC	SF1147	LUBRICANT
GENERAL ELECTRIC	F50	HIGH TEMP LUBRICANT
GENERAL ELECTRIC	SF1265	POLYDIMETHYLDIPHENYLSILOXANE
HOECHST UK LTD	HOSTINERT 130,175,216,272	PERFLUORINATED LIQ. COMPOSED OF CARBON, FLUORINE, & OXYGEN ATOMS
MONSANTO	THERMINOL LT	SYNTHETIC AROMATIC FLUID
MONSANTO	THERMINOL 44	MODIFIED ESTER BASED FLUID

Table 11. (continued)

COMPANY	FLUID	FLUID DESCRIPTION
MONSANTO	THERMINOL 55	SYNTHETIC HYDROCARBON
MONSANTO	THERMINOL 59	ALKYL SUBSTITUTED AROMATIC
MONSANTO	THERMINOL 60	POLYAROMATIC COMPOUND
MONSANTO	THERMINOL 66	MODIFIED TERPHENYHL
MONSANTO	THERMINOL 75	TERPHENYL/QUATERPHYNYL
MONSANTO	THERMINOL VP1	EUTECTIC MIXTURE OF 73.5% DIPHELYOXIDE,26.5% BIPHENHYL
MULTITHERM	IG2	SINGLE-CUT PARAFFINIC
MULTITHERM	PG1	WHITE MINERAL OIL
UNION CARBIDE	UCAR FOODFREEZE 35	PROPYLENEGLYCOL BASED
UNION CARBIDE	UCARTHERM	ETHYLENE-GLYCOL BASED
UNION CARBIDE	UCAR TRITHERM	INHIBITED TRIETHYLENE GLYCOL-BASED
UNION CARBIDE	UCON 500	POLYALKALENE GLYCOL-BASED
UNION CARBIDE	L-305 SILICON FLUID	DIMETHYLPOLYSILOXANE

Table 11.(continued)

FLUID	PVAP (@293 K or T shown) (kPa)	NORMAL BOILING POINT (K)	FREEZING POINT (K)	FLASH POINT (K)	FIRE POINT (K)
FC72	30.9	309	183	NON FLAMMABLE	NON FLAMMABLE
FC84	10.5	353	178	NON FLAMMABLE	NON FLAMMABLE
FC77	5.6	370	163	NON FLAMMABLE	NON FLAMMABLE
FC104	3.9	374	208	NON FLAMMABLE	NON FLAMMABLE
FC75	4.1	375	185	NON FLAMMABLE	NON FLAMMABLE
FC40	0.4	428	216	NON FLAMMABLE	NON FLAMMABLE
FC43	0.17	447	223	NON FLAMMABLE	NON FLAMMABLE
FC5311	<0.013	488	253	NON FLAMMABLE	NON FLAMMABLE
FC70	<0.013	488	248	NON FLAMMABLE	NON FLAMMABLE
FC5312	<0.013	488	283	NON FLAMMABLE	NON FLAMMABLE
FC71	<0.0026	526	306	NON FLAMMABLE	NON FLAMMABLE
FC87	?	307	?	?	?
DEMEON 13/87	700 @ 298 K	244	?	NON FLAMMABLE	NON FLAMMABLE
GALDEN D/80	10.5 @298 K	357	?	NONFLAMMABLE	NONFLAMMABLE
GALDEN D02	<.13 @298 K	448	?	NONFLAMMABLE	NONFLAMMABLE
GALDEN D03	<.13 @ 298 K	463	?	NONFLAMMABLE	NONFLAMMABLE
GALDEN D05	<.13 @ 298 K	503	?	NONFLAMMABLE	NONFLAMMABLE
GALDEN D10	NIL @ 298 K	523	?	NONFLAMMABLE	NONFLAMMABLE
GALDEN D20	NIL @ 298 K	543	?	NONFLAMMABLE	NONFLAMMABLE
GALDEN D40	NIL @ 298 K	NONE @ 1 ATM	?	NONFLAMMABLE	NONFLAMMABLE
LS/215	NIL @ 298 K	488	?	NONFLAMMABLE	NONFLAMMABLE
LS/230	NIL @ 298 K	503	?	NONFLAMMABLE	NONFLAMMABLE
HS/260	NIL @ 298 K	533	?	NONFLAMMABLE	NONFLAMMABLE
SYLTHERM 800	NIL	473	233	308	341
SYLTHERM XLT	<0.27	443	180	320	?
DC200	NIL	>373	233	272 TO 588	?
DC510	NIL	?	223	272 TO 588	?
DC550	NIL	?	233	272 TO 588	?
DC710	NIL	?	255	272 TO 588	?
DCFS1265	NIL	?	233	272 TO 588	?
SF97-50	NOT GIVEN	NOT GIVEN	218	573	613
SF96-100	NOT GIVEN	NOT GIVEN	206	848	948
SF1154	NOT GIVEN	NOT GIVEN	233	823	923
SF1147	NOT GIVEN	NOT GIVEN	213	753	873
F50	NOT GIVEN	NOT GIVEN	173	823	913
SF1265	NOT GIVEN	NOT GIVEN	?	?	?
HOSTINERT 130,175,216,272	<0.1 TO 3	403 TO 545	<183	NON FLAMMABLE	>923

Table 11. (continued)

FLUID	PVAP (@293 K or T shown) (kPa)	NORMAL BOILING POINT (K)	FREEZING POINT (K)	FLASH POINT (K)	FIRE POINT (K)
THERMINOL LT	0.102	454	198	330	339
THERMINOL 44	NIL	>473	211	480	499
THERMINOL 55	NIL	>560	233	450	483
THERMINOL 59	NIL	588	205	423	443
THERMINOL 60	NIL	563	205	427	433
THERMINOL 66	NIL	>616	247	450	466
THERMINOL 75	NIL	>653	343	472	500
THERMINOL VP1	NIL	>523	285	397	400
IG2	7.4@588 K	621	255	500	533
PG1	56 @477 K	589	233	444	469
UCAR FOODFREEZE 35	0.09	435	222	372	NOT GIVEN
UCARTHERM	0.16	437.5	248.4	400.7	NOT GIVEN
UCAR TRITHERM	0.48	416.4	220	NONE	?
UCON 500	NIL	>533	233	588	?
L-305 SILICON FLUID	NIL	>533	213	511	>573

Table 11.(continued)

FLUID/COMMENTS

FC72
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC84
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC77
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC104
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC75
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC40
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC43
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC5311
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC70
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC5312
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC71
NON TOXIC BUT AT OR ABOVE 200 C THERMAL DEGRADATION MAY GENERATE HIGHLY TOXIC DECOMPOSITION PRODUCTS

FC87
NEW FLUID NOT IN BROCHURE, INFO FROM TELECON W/3M

DEMEON 13/87
NONTOXIC BUT STILL CONTAINS CFC , R12, WHICH MAY DECOMPOSE TO TOXIC SUBSTANCE.

Table 11. (continued)

FLUID/COMMENTS
GALDEN D/80 LOW TOXICITY, MAY BREAK DOWN AT HIGH TEMP
GALDEN D02 LOW TOXICITY, MAY BREAK DOWN AT HIGH TEMP
GALDEN D03 LOW TOXICITY, MAY BREAK DOWN AT HIGH TEMP
GALDEN D05 LOW TOXICITY, MAY BREAK DOWN AT HIGH TEMP
GALDEN D10 LOW TOXICITY, MAY BREAK DOWN AT HIGH TEMP
GALDEN D20 LOW TOXICITY, MAY BREAK DOWN AT HIGH TEMP
GALDEN D40 LOW TOXICITY, MAY BREAK DOWN AT HIGH TEMP
LS/215 LOW TOXICITY, MAY BREAK DOWN AT HIGH TEMP
LS/230
HS/260 LOW TOXICITY, MAY BREAK DOWN AT HIGH TEMP
SYLTHERM 800 LOW TOXICITY,DESIGNED FOR USE AS HIGH TEMP LIQ PHASE HEAT TRANSFER FLUID
SYLTHERM XLT LOW TOXICITY,DESIGNED AS LIQUID PHASE HEAT TRANSFER FLUID
DC200 GENERAL PURPOSE SILICONE FLUID,MARKETED AS LOW FREEZE PT, VERY LOW VAP PRESS,AND HIGH FLASH PTS.(FLASH POINTS VARY WITH VISCOSITY)

Table 11. (continued)

FLUID/COMMENTS
DC510 GENERAL PURPOSE SILICONE FLUID,MARKETED AS LOW FREEZE PT, VERY LOW VAP PRESS,AND HIGH FLASH PTS.(FLASH POINTS VARY WITH VISCOSITY)
DC550 GENERAL PURPOSE SILICONE FLUID,MARKETED AS LOW FREEZE PT, VERY LOW VAP PRESS,AND HIGH FLASH PTS.(FLASH POINTS VARY WITH VISCOSITY)
DC710 GENERAL PURPOSE SILICONE FLUID,MARKETED AS LOW FREEZE PT, VERY LOW VAP PRESS,AND HIGH FLASH PTS.(FLASH POINTS VARY WITH VISCOSITY)
DCFS1265 GENERAL PURPOSE SILICONE FLUID,MARKETED AS LOW FREEZE PT, VERY LOW VAP PRESS,AND HIGH FLASH PTS.(FLASH POINTS VARY WITH VISCOSITY)
SF97-50 DESIGNED AS DIELECTRIC FLUID;PUBLICATION INDICATES INDEFINITE OPERATION AT 150 C. THEREFORE,LIKELY HIGH BOILING POINT. LOW TOXICITY
SF96-100 USED IN RADIATION ENVIRON.,HIGH BOILING POINT
SF1154 USED IN RADIATION ENVIRON.,HIGH BOILING POINT
SF1147 USED IN RADIATION ENVIRON.,HIGH BOILING POINT
F50 USED IN RADIATION ENVIRON.,HIGH BOILING POINT
SF1265 INTERNAL RELEASE AGENT FOR RESINS
HOSTINERT 130,175,216,272 NON-TOXIC, MFR CLAIMS STABILITY AT HIGH TEMPERATURE
THERMINOL LT

Table 11. (continued)

FLUID/COMMENTS
THERMINOL 44
THERMINOL 55
THERMINOL 59
THERMINOL 60
THERMINOL 66
THERMINOL 75 SOLID AT ROOM TEMP
THERMINOL VP1 RELATIVELY HIGH POUR POINT
IG2 NONTOXIC, HIGH TEMP HT TRANSF FLUID
PG1 NONTOXIC, HIGH TEMP HT TRANSF FLUID, FDA/USDA CERTIFIED
UCAR FOODFREEZE 35 USED IN FOOD PROCESSING
UCARTHERM
UCAR TRIT
L-305 SILICON FLUID

APPENDIX A. DETAILS OF CALCULATION

Background

Forced-convection boiling (or condensation) in horizontal tubes was considered to be the primary mechanism of heat transfer for the calculations of this study. In order to calculate the thermal performance ranking parameters, FOMB and FOMC, it was necessary to select appropriate correlations for the prediction of the boiling (or condensation) heat transfer coefficient and the two-phase pressure drop (and thus the corresponding pumping power required to circulate the fluid). The primary reference source for the selection of correlations and for other two-phase flow background information was Collier [13].

We tacitly assumed that the relative ranking of the fluids for thermal performance is primarily dependent on the fluid properties (as they arise in the heat transfer and pressure drop correlations) and not on the system geometry and/or boundary conditions chosen for thermal performance evaluation. However, the effect of D, L/D, and Reynolds number was initially examined for a few fluids. The results showed that the relative ranking was essentially the same. Therefore, in order to limit the number of data files/records to a manageable size, we have performed the detailed calculations and resulting ranking and sorting for a uniformly heated pipe of diameter, D=0.02 m, and length-to-diameter ratio, L/D=100. The results for two different liquid Reynold numbers (2000 and 200 000 - turbulent flow region) are included. These assumptions and others are implied in Figure A1. We shall note additional assumptions in the discussions to follow.

Flow Regime and Heat Transfer Correlations

As a saturated liquid flowing through a pipe is subjected to a uniform heat flux, various flow patterns will develop in the pipe. A particularly important flow pattern is annular flow since it may occur over a wide range of mass quality (x from 0.1 and below, up to 1) [13]. Also, this flow pattern is one likely to dominate in zero-g [14]. Therefore, we assumed this flow regime to be representative and sought correlations applicable to it.

Boiling

There are a number of correlations in the literature for predicting the heat transfer coefficient in the regions of saturated nucleate boiling and forced convective heat transfer through a liquid film. These regions are usually associated with the annular flow pattern. Collier [13], however, has recommended the Chen correlation. This correlation is a superposition one where it is presumed that the contributions from nucleate boiling, h^{NuB}, and forced convection, h_c, are additive; that is,

$$h_{tp}=h_{NuB}+h_c \tag{A1}$$

where

$$h_{NuB} = 0.00122\left[\frac{k_l^{0.79}\, C_{p,l}^{0.45}\, \rho_l^{0.49}}{\sigma^{0.5}\, \mu_l^{0.29}\, \Delta H^{0.24}\, \rho_g^{0.24}}\right] * \Delta T_{sat}^{0.24} \Delta p_{sat}^{0.75}\, S \tag{A2}$$

and

$$h_c = 0.023 \left[\frac{k_l}{D}\right]\left[\frac{G(1-x)D}{\mu_l}\right]^{0.8} \left[\frac{C_p \mu}{k}\right]_l^{0.4} F. \tag{A3}$$

The correction factors F and S have been empirically determined as:

$$(F) = f_1(\chi_{tt}), \tag{A4}$$

and

$$(S) = f_2(Re_{tp}). \tag{A5}$$

The Martinelli-Nelson parameter is defined as:

$$\chi_{tt}^2 = \frac{\left[\frac{dp}{dz}\right]_{f,l}}{\left[\frac{dp}{dz}\right]_{f,v}} \tag{A6}$$

where the subscript "f" indicates the pressure gradient is due to friction losses. χ_{tt} may be approximated by

$$\chi_{tt} \approx \left[\frac{1-x}{x}\right]^{0.9} \left[\frac{\rho_v}{\rho_l}\right]^{0.5} \left[\frac{\mu_l}{\mu_v}\right]^{0.4} \tag{A7}$$

The two-phase Reynolds number is defined as:

$$Re_{tp} = F^{1.25} Re_l, \tag{A8}$$

where

$$Re_l = \frac{G(1-x)D}{\mu_l} .$$

The functions F and S are presented in graphical form [10]. We fit the curves in the graphs with equations of the form:

$$\log_{10} F = A_F+B_F(\log_{10}(1/\chi_{tt}))+C_F(\log_{10}(1/\chi_{tt}))^2+ D_F(\log_{10}(1/\chi_{tt}))^3 \tag{A9}$$

$$S = A_S+B_S\log_{10}(Re_{tp})+C_S(\log_{10}(Re_{tp}))^2+D_S(\log_{10}(Re_{tp}))^3 \tag{A10}$$

Condensation

The correlation used for condensation heat transfer, h_{cond}, in horizontal tubes for annular flow was developed by Breber, et al. [15]

$$h_{cond} = h_l(\phi_l^2)^{0.45} \tag{A11}$$

where

$$h_l = 0.023(Re_l)^{0.8}(Pr_l)^{0.4}(k_l/D), \tag{A12}$$

and Φ_l is the two-phase friction multiplier which may be expressed in the form

$$\Phi_l^2 = 1+(C/\chi_{tt})+(1/(\chi_{tt})^2) \tag{A13}$$

For turbulent-turbulent gas-liquid flow, C=20.

Two-phase Pressure Drop

A separated flow model of the two-phase vapor-liquid flow in the pipe was assumed in the calculation of the two-phase pressure drop. Collier [13] gives the following expression for the particular case where a fluid is evaporated from a liquid at the saturation temperature (x=0) to a vapor-liquid mixture containing a mass quality xL, with a linear change of x over a length L (dx/dz=constant):

$$\Delta p_{tp} = \Delta p_f + \Delta p_a + \Delta p_g \tag{A14}$$

$$\Delta p_f = \frac{2 f_{fo} G^2 v_l L}{D} \left[\frac{1}{x_L} \int_0^{x_L} \Phi_{lo}^2 dx \right] \tag{A15}$$

$$\Delta p_a = G^2 v_l \left[\frac{x_L^2}{\alpha} \left[\frac{v_v}{v_l} \right] + \frac{(1-x_L)^2}{(1-\alpha)} - 1 \right] \tag{A16}$$

$$\Delta p_g = \frac{L \, g \, \sin\theta}{x_L} \int_0^{x_L} (\rho_v \alpha + \rho_l (1-\alpha)) dx \tag{A17}$$

For complete vaporization of the liquid stream, and ignoring the gravity term (g=0), eq.(A14) becomes:

$$\Delta p_{tp} = \frac{2 f_{fo} G^2 v_l L}{D} \left[\int_0^1 \Phi_{lo}^2 dx \right] + G^2 (v_v - v_l) \tag{A18}$$

where f_{fo} is the friction factor when the total flow is all liquid.

$$f_{fo} = \frac{0.079}{(GD/\mu_l)^{0.25}} \tag{A19}$$

and

$$\Phi_{lo}^2 = \Phi_l^2 (1-x)^{1.75} \tag{A20}$$

A numerical integration was performed for the term $\int_0^1 \Phi_{lo}^2 dx$.

The absolute value of the total two-phase pressure drop for condensation was considered to be the same as that calculated for boiling.

Calculation Procedure

The Fortran computer program which performs these calculations is given at the end of this appendix (Supplement 1); The methodology for the calculations follows:

(1) Read the thermodynamic and transport properties for one of the candidate fluids in the temperature ranges. These data are stored in an array for four different bulk temperatures within the ranges. If a property was not available at the bulk temperature, then the calculations were not performed for that fluid at that temperature. This was frequently the case in Temperature Range 1 at 200 K.

(2) Perform an in-situ least squares fit of the vapor pressure data for each fluid. This is required for the iterative solution of the Chen correlation (Δp_{sat} term).

(3) Input the system geometry data, D, L/D.

(4) Call the calculation subroutine for each of the four bulk temperatures. The calculations consist of the following steps for each of two liquid Reynolds numbers (at entrance to pipe, 2000 and 200 000):

(a) Calculate the mass velocity, $G = \mu_l Re/D$

(b) Calculate the Martinelli correlating parameter, χ_{tt}, at 11 points along the tube ($0.01 <= x <= 0.99$, ten intervals assuming that for a uniform heat flux, quality varies linearly along the length of the tube). Store the local values in an array for later numerical integration to calculate an average.

(c) Calculate the correction factor, F for the Chen correlation.

(d) Calculate the two-phase Reynolds number, $Re_{tp}=Re_l * F^{1.25}$, and the correction factor, S for the Chen correlation.

(e) Calculate the heat flux required to completely vaporize the liquid stream over the length of the pipe.

$$q_0 = \left[\frac{G\ \Delta H}{4\ (L/D)}\right] + \left[\frac{1*10^{-7} D G^3}{8L}\right]\left[\frac{1}{\rho_v{}^2} - \frac{1}{\rho_l{}^2}\right] \qquad \text{(A21)}$$

(f) Calculate the two-phase forced-convection boiling-heat transfer coefficient using the Chen correlation; an iterative procedure is required since ΔT_{sat} and Δp_{sat} are not known. This calculation is done for each of the 11 stations along the tube ($0.01 =< x <= 0.99$) and the local

values are stored in an array.

(g) Perform the same calculations as above for condensation, and store the local values of heat transfer coefficient in an array.

(h) Integrate the local boiling and condensing heat transfer coefficients over the length of the tube to get an average value. This average value is used in FOMB and FOMC.

(i) Integrate the local Martinelli correlating parameter, χ_{tt}, over the length of the tube to get an average value. This average value is used in calculating an average volume fraction of vapor, α.

(j) Calculate the total two-phase pressure drop.

(k) Calculate the power per unit surface area required to circulate the fluid through the tube. Here we used a homogeneous model to calculate an average volume fraction, α, and thus average density of the two-phase mixture.

$$\Phi_l^2 = 1+(20/\chi_{tt})+(1/(\chi_{tt})^2) \qquad \text{(A22)}$$

$$\alpha = 1-\left[\Phi_l^2\right]^{-0.5} \qquad \text{(A23)}$$

$$\rho_{mix} = \alpha\rho_v+(1-\alpha)\rho_l \qquad \text{(A24)}$$

and

$$PUMPWR = \Delta p_{tp} G/(4\ \rho_{mix}\ L/D) \qquad \text{(A25)}$$

(l) Calculate the ratio of heat flux to pumping power per unit surface area (COPB)

(m) Calculate the ratio of heat transfer coefficient to pumping power per unit surface area (FOMB and FOMC).

(n) Print the output and repeat for the next fluid.

Detail on Calculation of Ranking Factors, (WF**)**

We calculated the cumulative relative-frequency distribution of the values of the parameters noted in the text. This procedure eliminates the need to scan the entire column of data within a column to determine the relative ranking of a particular fluid. It also provides a means of putting the parameters on the same basis so that an overall ranking of a fluid may be obtained by addition of the ranking factors. Because frequently the values of the parameters varied over several orders of magnitude the logarithm of each value was calculated and the cumulative relative-frequency determined on this basis.

If for a certain parameter value, x, we tally and then sum all the frequencies corresponding to parameter values which are smaller than or equal to that x, we obtain the cumulative frequency corresponding to that x. Division by the total number of fluids yields the cumulative relative frequency [9]. This number we have called "ranking factor" and accordingly it varies between 0 and 1. A ranking factor of 1 indicates that 100% of the parameter values are less than or equal to that x. The task becomes one of forcing the "preferred" value for each parameter to be the maximum value so that the cumulative relative frequency represents the proximity to the preferred value whether the preferred value is the maximum value, (for example, FOMB, LTF) a fixed value (for example, 101 kPa for PVAP, and 293 K for NBP) or the minimum value (for example TMP, and DEN). This was done as described below:

<u>WFFOMB and WFLTF (Ranking Factors for Figure of Merit for Boiling and Liquid Transport Factor)</u>

For these parameters the preferred value was the maximum value. That is, the ratio of heat transfer coefficient to required pumping power should be large and the liquid transport factor should be large. In this case the calculation of culumulative relative frequency was straightforward and it was not required to force the preferred value to be the maximum.

WFNBP and WFPVAP (Ranking Factors for Normal Boiling-point and Operating Pressure at Tbulk)

The preferred value for the normal boiling-point was 293 K (20°C). We chose this value because by definition, the vapor-pressure at this temperature is 101 kPa (1 atm). This criterion (proximity to 1 atm at "room temperature") arises from the concern for possible leakage into (or out of) the thermal control loop and the crew modules which are nominally maintained at 293 K and 101 kPa (1 atm). Therefore, if the heat transport fluid in the thermal control loop has a NBP near 293 K there is less potential driving force for leakage into or out of the system.

For calculation of ranking factor, WFNBP, the NBP of each fluid was divided by 293 K, and the logarithm of the ratio was calculated. The desired value was therefore 0 (that is, log 1=0), and this implies NBP=293 K. For assignment of ranking factor, we are interested in the proximity to 293 K, not whether the NBP is greater than or less than 293 K. In order to "force" the preferred value to the maximum value, if log(NBP /293) > 0, then change its sign,

$$\log_{10}(NBP/293) \text{ becomes } -\log_{10}(NBP/293)$$

and all values appear to be less than or equal to 0; 0 is then the maximum value and the preferred value. Those fluids having NBP furthest away from 293 K have large negative numbers and by the cumulative relative frequency calculation receive a ranking factor of 0 or a very small number; those closest to 293 K have small negative numbers and are assigned a ranking factor near 1.

For calculation of ranking factor, WFPVAP, the vapor pressure at T_{bulk} of each fluid was divided by 101 kPa (1 atm) and the corresponding logarithm of the ratio calculated. Analagous to the procedure for WFNBP assignment, we determined the ranking factors, WFPVAP, for each fluid.

WFTMP and WFDEN (Ranking Factors for Melting-point and Liquid Density)

The preferred values for both these parameters is the minimum value. A low melting-point (or freezing point) minimizes the possibility of freeze-up in the lines under off-normal conditions. All other factors being equal, a small liquid density translates to a small system mass, important in spacecraft application.

The logarithm of each value was calculated and the cumlulative relative frequency calculated. Since we want the minimum value to receive a ranking factor of 1, then set:

$$WF = 1. - CUM.\ REL.\ FREQ.$$

In this fashion, the fluids having the lowest melting-points and liquid densities receive the highest ranking factor.

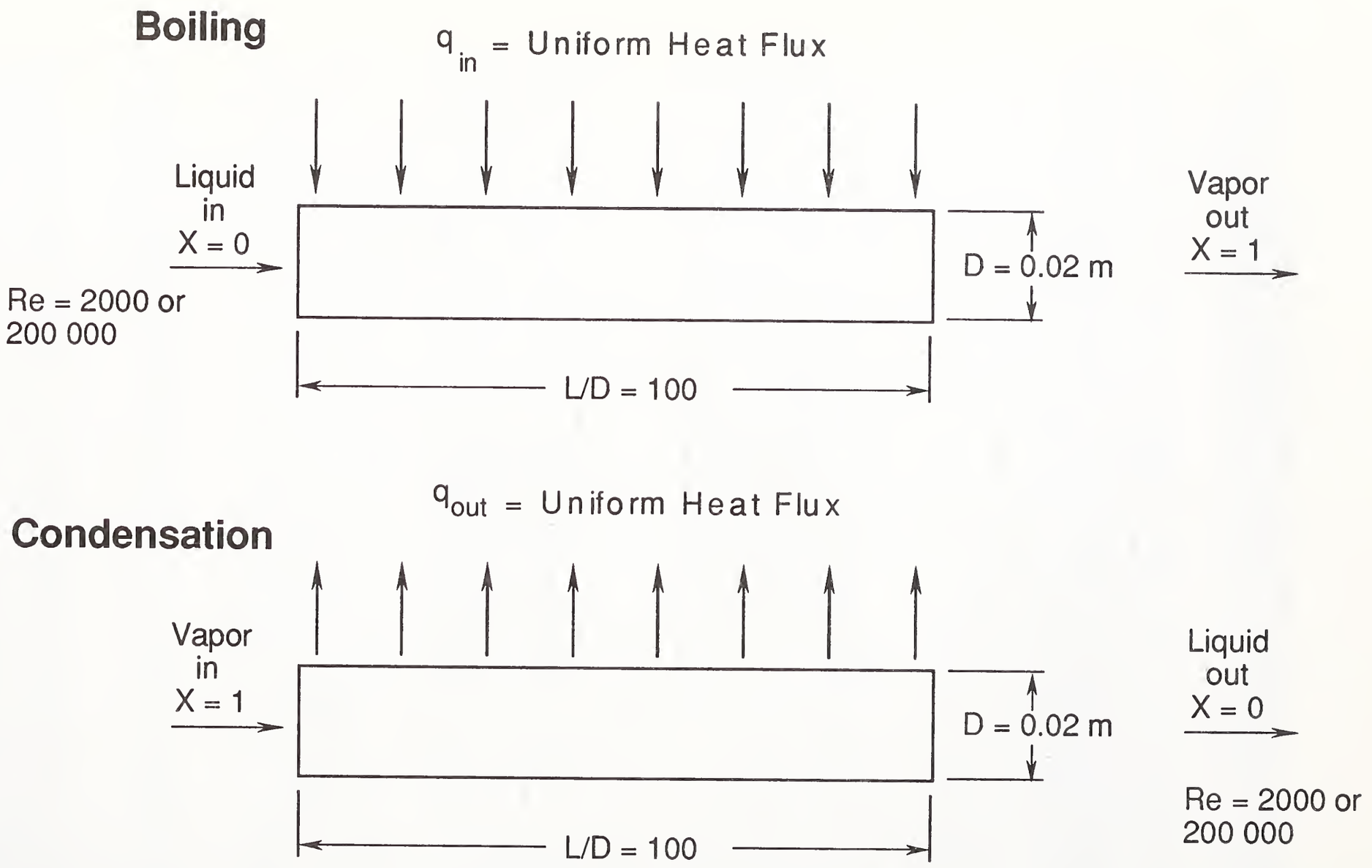

Figure A1 - Assumed Geometry and Conditions for Evaluating Thermal Performance Parameters, FOMB, FOMC.

Supplement A1. Computer Program for Calculation of Thermal Performance Parameters.

```
                PROGRAM COP1AVG
C THIS PROGRAM PERFORMS CALCS FOR ENVELOPE1(USES AVG HT
C COEFFICIENT IN THE PIPE)
                DIMENSION TBULK(4),RHOL(4),RHOV(4),VISCL(4),
     1 VISCV(4),CPL(4),CPV(4),TCONL(4),TCONV(4),
     2 SURTEN(4),XLATHT(4),PSATB(4),TR(4),PR(4)
                DIMENSION COEF(2),QUAL(3)
                CHARACTER XNAME*32,FMLA*12,TEST*1
                COMMON/DATA/TBULK,RHOL,RHOV,VISCL,VISCV,CPL,
     1 CPV,TCONL,TCONV,SURTEN,XLATHT,PSATB,
     2 D,XLEN,TCRIT,PCRIT,TBP
                COMMON/LSQ/COEF

C**********************************
C               READ SYSTEM PARAMETERS FROM UNIT 5
C               READ PROPERTIES DATA FROM UNITS 6,7,8,9,10
C               UNIT 6 WILL HAVE TRANSPORT PROPS ALONG SAT LINE AT T1
C               UNIT 7 WILL HAVE PROPS ALONG SAT LINE AT T2
C               UNIT 8 WILL HAVE PROPS ALONG SAT LINE AT T3
C               UNIT 9 WILL HAVE PROPS ALONG SAT LINE AT T4
C               UNIT 4 WILL HAVE PHYS PROP DATA INCLUDING NORMAL BP,
C               MELTING POINT, TCRIT,PCRIT
C*********UNIT 12 WILL CONTAIN OUTPUT
C*************INPUT SYSTEM PARAMETERS
                OPEN (12,FILE="OUTPUT.DAT",STATUS="UNKNOWN")
                OPEN (4,FILE="SORTID.EN1",STATUS="OLD")
                OPEN(6,FILE="ENV1200.DAT",STATUS="OLD")
                OPEN(7,FILE="ENV1250.DAT",STATUS="OLD")
                OPEN (8,FILE="ENV1300.DAT", STATUS="OLD")
                OPEN (9,FILE="ENV1350.DAT", STATUS="OLD")
C*****READ INPUT DATA FROM FILES
                NREAD=0
    5 CONTINUE
                NREAD=NREAD+1
                WRITE(*,*)NREAD
C               IF(NREAD.EQ.50)GO TO 2500

                READ(4,1500,END=2500,ERR=9004)
     1 ID1,XNAME,FMLA,FW,TMP,TBP,TCRIT,
     1          PCRIT
C               CLOSE (4)
                READ (6,1000,END=2500,ERR=9006)ID2,FMLA,
     1 TBULK(1),RHOL(1),
     1 RHOV(1),CPL(1),CPV(1),TCONL(1),TCONV(1),
     2 VISCL(1),VISCV(1),XLATHT(1),SURTEN(1),PSATB(1)
C               CLOSE (6)
                IF(ID1.NE.ID2)THEN
          WRITE(*,*)"ERROR,IDS NOT EQUAL"
                GO TO 2500
                ELSE
                ENDIF
                READ (7,1000,END=2500,ERR=9007)ID2.FMLA.
```

```
     1 TBULK(2),RHOL(2),
     1 RHOV(2),CPL(2),CPV(2),TCONL(2),TCONV(2),
     2 VISCL(2),VISCV(2),XLATHT(2),SURTEN(2),PSATB(2)
C                CLOSE (7)
                 IF(ID1.NE.ID2)THEN
          WRITE(*,*)"ERROR,IDS NOT EQUAL"
                 GO TO 2500
                 ELSE
                 ENDIF
                 READ (8,1000,END=2500,ERR=9008)ID2,FMLA,
     1 TBULK(3),RHOL(3),
     1 RHOV(3),CPL(3),CPV(3),TCONL(3),TCONV(3),
     2 VISCL(3),VISCV(3),XLATHT(3),SURTEN(3),PSATB(3)
C                CLOSE (8)
                 IF(ID1.NE.ID2)THEN
          WRITE(*,*)"ERROR,IDS NOT EQUAL"
                 GO TO 2500
                 ELSE
                 ENDIF
                 READ (9,1000,END=2500,ERR=9009)ID2,FMLA,
     1  TBULK(4),RHOL(4),
     1 RHOV(4),CPL(4),CPV(4),TCONL(4),TCONV(4),
     2 VISCL(4),VISCV(4),XLATHT(4),SURTEN(4),PSATB(4)
C                CLOSE (9)
                 IF(ID1.NE.ID2)THEN
          WRITE(*,*)"ERROR,IDS NOT EQUAL"
                 GO TO 2500
                 ELSE
                 ENDIF
 1000 FORMAT(1X,I3,1X,A12,F6.1,F7.1,F8.2,2F5.2,F6.4,
     1 F7.5,F7.3,F7.5,F7.1,F7.5,F7.1)
 1020 FORMAT(16X,F6.1,F7.1,F8.2,2F5.2,F6.4,
     1 F7.5,F7.3,F7.5,F7.1,F7.5,F7.1)
 1500 FORMAT(I3,3X,A32,2X,A12,F6.1,3F8.1,F8.0)
C CHECK TO SEE THAT VAPOR PRESSURES ARE REASONABLE
                 IF(PSATB(4).LT.0.1)THEN
                 GO TO 5
      ENDIF
                 DO 1625 I=1,4
                 IF(PSATB(I).LT.0.1)THEN
                 GO TO 1625
                 ENDIF
                 IF(PSATB(I).GE.0.1)THEN
C CHECK TO SEE THAT ALL DATA ARE AVAILABLE FOR THE SUBSTANCE
C EXCEPT FOR CPV AND TCONV WHICH AREN'T USED IN CALCS
                 PROD=RHOL(I)*RHOV(I)*CPL(I)
     1*TCONL(I)*VISCL(I)*VISCV(I)
     2*XLATHT(I)*SURTEN(I)
                 ENDIF
                 IF(PROD.EQ.0.)GO TO 5
 1625 CONTINUE
      WRITE(*,1610)ID1,FMLA,XNAME
 1630 WRITE(12,1611)
      WRITE(12,1610)ID1,FMLA,XNAME
C1610 FORMAT(/,'ID NO.=',I3/1X,A12,A32)
 1610 FORMAT(1X,I3,/1X,A12,A32)
 1611 FORMAT('++++++')
```

```
C  CONVERT KILOJOULES TO JOULES IN CP
                DO 1550 I=1,4
                CPL(I)=CPL(I)*1000.
                CPV(I)=CPV(I)*1000.
 1550           CONTINUE
C  CONVERT KILOJOULES TO JOULES IN LATENT HEAT
                DO 1560 I=1,4
                XLATHT(I)=XLATHT(I)*1000.
 1560 CONTINUE
C CONVERT CENTIPOISE TO PaS IN VISCOSITY
                DO 1570 I=1,4
                VISCL(I)=VISCL(I)*0.001
                VISCV(I)=VISCV(I)*0.001
 1570 CONTINUE
C  CONVERT KILOPASCALS TO PASCALS
                DO 1600 I=1,4
                PSATB(I)=PSATB(I)*1.E3
 1600 CONTINUE
                PCRIT=PCRIT*1.E3
C  CALCULATE REDUCED TEMPERATURES AND PRESSURES
                DO 1612 KK=1,4
                TR(KK)=TBULK(KK)/TCRIT
                PR(KK)=PSATB(KK)/PCRIT
C DO THE FOLLOWING FOR PRINTOUT CONVENIENCE
                PSATB(KK)=PSATB(KK)/1000.
                WRITE(12,1640)TBULK(KK),PSATB(KK),RHOL(KK),
     1 TR(KK),PR(KK)
C GET UNITS BACK AGAIN
                PSATB(KK)=PSATB(KK)*1000.
 1612 CONTINUE

C 1640 FORMAT('TBULK (K)=',F6.1,2X,
C     1  'VAPOR PRESSURE (Pa)=',G10.3,2X,
C     2  'LIQUID DENSITY (KG/M3)=',G10.3,3X,/
C     3  'REDUCED TEMP=',G10.3,3X,'REDUCED PRESS=',G10.3,/)
 1640 FORMAT(F6.1,2X,F10.3,F10.3,F10.4,3X,F10.4,/)
C  PERFORM LEAST SQUARES FIT OF VAPOR PRESSURE VS T
C  THE ARRAY C CONTAINS THE COEFFICIENTS OF THE FIT
C LOG P=C(1)+C(2)/T
C THIS WILL BE USED IN THE CALC OF PSAT CORRES TO TWALL
C  WHICH IS NEEDED IN THE CHEN BOILING CORRELATION

                 CALL LSQ2D(COEF)



                 OPEN(5,FILE="SYSPAR.DAT",STATUS="OLD")
 1615  READ (5,*,END=2000,ERR=9005)D,XLOD
                XLEN=XLOD*D
                WRITE(12,1605)D,XLOD
C 1605 FORMAT(3X,'D (M)=',F8.3,3X,'L/D=',F8.3,//)
 1605 FORMAT(3X,F8.3,3X,F8.3//)

       DO 1950 I=1,4
```

```
                IF(PSATB(I).LT.100.)THEN
       GO TO 1950
                ENDIF
C               CALL SUBROUTINE FOR CALCULATIONS AND PRINTING
                 CALL CALC(TBULK(I),RHOL(I),
     1 RHOV(I),CPL(I),CPV(I),TCONL(I),TCONV(I),
     2 VISCL(I),VISCV(I),XLATHT(I),SURTEN(I),PSATB(I),
     3 ID1)
 1950 CONTINUE
                GO TO 1615
 2000           CLOSE (5)
                GO TO 5
 2500           CLOSE (12)
                CLOSE (6)
                CLOSE (7)
                CLOSE (8)
                CLOSE (9)
                GO TO 10000
 9004 WRITE(*,*)"ERROR IN TAPE 4"
                READ(4,FMT='(A)')TEST
                READ(6,FMT='(A)')TEST
                READ(7,FMT='(A)')TEST
                READ(8,FMT='(A)')TEST
                READ(9,FMT='(A)')TEST
                GO TO 5
C      GO TO 10000
 9005 WRITE(*,*)"ERROR IN TAPE 5"
                GO TO 5

C               GO TO 10000
 9006  WRITE(*,*)"ERROR IN TAPE 6"
                READ(6,FMT='(A)')TEST
                READ(7,FMT='(A)')TEST
                READ(8,FMT='(A)')TEST
                READ(9,FMT='(A)')TEST
                GO TO 5
C               GO TO 10000
 9007 WRITE(*,*)"ERROR IN TAPE 7"
                READ(7,FMT='(A)')TEST
                READ(8,FMT='(A)')TEST
                READ(9,FMT='(A)')TEST
                GO TO 5
C               GO TO 10000
 9008 WRITE(*,*)"ERROR IN TAPE 8"
                READ(8,FMT='(A)')TEST
                READ(9,FMT='(A)')TEST
                GO TO 5
C               GO TO 10000
 9009 WRITE(*,*)"ERROR IN TAPE 9"
                READ(9,FMT='(A)')TEST
                GO TO 5
10000 CONTINUE
      END
```

```
*********************************************************
                SUBROUTINE CALC(TBULK,RHOL,RHOV,CPL,CPV,TCONL,TCONV,
     1            VISCL,VISCV,XLATHT,SURTEN,PSATB,ID)
                DIMENSION G(2),REL(2)
                DIMENSION XHB(0:10),XHC(0:10),XTTS(0:10)
                COMMON/DATA/DUM(48),D,XLEN,DUM2(3)

               DATA REL/2.E03,2.E05/
                 DATA XMIN,XMAX/0.01,0.99/
                DATA A,B,C,DD,ABAR,BBAR,CBAR,DBAR/0.9946102006E+00,
     1  0.5913534234E+00,0.5548497826E-01,
     2  -0.5863304243E-02,-0.1883211071E+02,
     3  0.5806947612E+01,-0.5516715499E+00,
     4  0.1669278595E-01/


C**CALCULATE THE G(K) CORRESPONDING TO REYNOLDS
C**   NUMBERS OF 10E4,10E5,10E6---TURBULENT FLOW
C     AND THEN CALCULATE THE AVG HEAT TRANSFER COEFF
                DO 600 K=1,2


                 G(K)=VISCL*REL(K)/D
C CALCULATE THE HEAT TRANSFER COEF FOR 11 STATIONS (I.E.,
C  FOR 0.01>=X<=0.99 TEN INTERVALS)
                DO 135 JJ=0,10
                XINTER=(XMAX-XMIN)/10.
                X=XMIN+XINTER*REAL(JJ)
C CALCULATE THE XTT(MARTINELLI-NELSON CORRELATING PARAMETER)
                XTT=((1.-X)/(X))**0.9*(VISCL/VISCV)**0.1
     1 *(RHOV/RHOL)**0.5
C STORE XTT IN AN ARRAY XTTS(11) FOR LATER AVERAGING
                XTTS(JJ)=XTT
C  CALCULATE 1/XTT

                XTTINV=1./XTT
C CALCULATE F  THE CORRECTION FACTOR WHICH ACCOUNTS FOR
C INCREASED TURBULENCE DUE TO PRESENCE OF VAPOR
                XX=ALOG(XTTINV)
                F=A+B*XX+C*XX**2+
     1 DD*XX**3
                F=EXP(F)
C CALCULATE THE TWO-PHASE RE NUMBER
C CALCULATE THE REYNOLDS NO. BASED ON LIQUID ALONE FLOW
C  RELF

                RELF=G(K)*(1.-X)*D/VISCL

                RETP=RELF*F**1.25
C               CALCULATE SUPPRESSION FACTOR,S
                 XX=ALOG(RETP)
                 S=ABAR+BBAR*XX+CBAR*XX**2
     1  +DBAR*XX**3

  125           CONTINUE
```

```
C CALCULATE THE FORCED CONVECTION BOILING HEAT TRANSFER
C    COEFFICIENT (ASSUMING  ANNULAR FLOW MODEL, I.E.
C    SEPARATED FLOW MODEL)
C       CHEN CORRELATION WILL BE USED

  130 CALL HTBOIL(XHTPB,XHTFLX,TDELT,G(K),F,S,
     1 CPL,VISCL,VISCV,TCONL,
     2 RELF,D,XLATHT,SURTEN,RHOL,RHOV,TBULK,X,XLEN,PSATB)
C STORE THE LOCAL BOILING HEAT TRANSFER COEFF IN AN ARRAY
                XHB(JJ)=XHTPB

C CALCULATE THE FORCED CONVECTION CONDENSATION HEAT TRANSFER
C  COEFFICIENT (CORRELATION FOR BUBBLE FLOW OR ANNULAR
C  FLOW INSIDE HORIZONTAL TUBES) REF: BREBER,PALEN,TABORED
C
                CALL HTCOND(XHTPC,XTT)
C STORE THE LOCAL CONDENSING HEAT TRANSFER COEFF IN
C AN ARRAY
                XHC(JJ)=XHTPC
135   CONTINUE

C INTEGRATE THE LOCAL BOILING HEAT TRANSFER COEFF OVER THE   C LENGTH OF THE PIPE TO GET AN AVERAGE
VALUE XHAVGB

                CALL SIMPSON(XHB,XINTER,XHAVGB)
C INTERGRATE THE LOCAL XTT OVR THE LENGTH OF THE PIPE
C TO GET AN AVERAGE VALUE XTTAVG
                CALL SIMPSON(XTTS,XINTER,XTTAVG)

C INTEGRATE THE LOCAL CONDENSING HEAT TRANSFER COEFF OVER
C LENGTH OF THE PIPE TO GET AN AVERAGE VALUE XHAVGC

                CALL SIMPSON(XHC,XINTER,XHAVGC)
C               CALCULATE THE TOTAL TWO-PHASE PRESSURE DROP OVER
C THE HEATED LENGTH (REF COLLIER PAGE 37).  THIS IS
C  FOR COMPLETE VAPORIZATION OF THE FLUID I.E. X=0 TO 1

  150           CALL DELTAP(1.,D,G(K),XLEN,DPTP,RHOL,
     1    RHOV,VISCL)


C               CALCULATE POWER PER UNIT SURFACE AREA REQUIRED
C      TO CIRCULATE FLUID THROUGH PIPE
C     USE HOMOGENEOUS MODEL TO CALCULATE AN AVERAGE VELOCITY
C     OF THE TWO- PHASES I.E. CALC VMIX=G(K)/RHOMIX
C   RHOMIX IS AVG VALUE IN PIPE BASED ON AVG ALPHA(AVG VOL
C    FRACTION OF VAPOR IN THE PIPE)
C  FIRST CALCULATE AN AVG ALPHA FROM PHILTTAVG USING XTTAVG
                PHILTTA=1.+20./XTTAVG+(1./XTTAVG**2)
                ALPHA=1.-(1./SQRT(PHILTTA))
  200           RHOMIX=ALPHA*RHOV+(1.-ALPHA)*RHOL
  250           PUMPPWR=DPTP*G(K)/(4.*RHOMIX*XLEN/D)



C
C CALCULATE RATIO OF BOILING HEAT FLUX INPUT
```

```
C   TO PUMPING POWER PER UNIT SURFACE AREA (COEFFICIENT OF
C   PERFORMANCE FOR BOILING)

  350           COPB=XHTFLX/PUMPPWR
C CALCULATE RATIO OF HEAT TRANSFER COEF TO PUMPING POWER PER C  UNIT SURFACE AREA (FIGURE OF MERIT
FOR BOILING)

                FOMB=XHAVGB/PUMPPWR
C CALCULATE THE CONDENSATION HEAT FLUX.  THIS IS THE SAME AS
C BOILING HEAT FLUX SINCE WE CONSIDER TOTAL COND. FROM X=1
C TO X=0
                CHTFLX=XHTFLX
                TDELTC=CHTFLX/XHC(10)
C  CALCULATE THE RATIO OF CONDENSATION HEAT TRANSFER COEF
C  TO PUMPING POWER PER UNIT SURFACE AREA (FIGURE OF MERIT  C  FOR CONDENSATION)

                FOMC=XHAVGC/PUMPPWR

C DIVIDE BY CONVENIENT FACTORS FOR PRINTOUT
                IF(REL(K).EQ.2.E05)THEN
                  PCOPB=COPB*1.E03
                  PFOMB=FOMB*1.E03
                  PFOMC=FOMC*1.E03
                ELSE
                  PCOPB=COPB
                  PFOMB=FOMB
                  PFOMC=FOMC
                ENDIF
                PXHTPB=XHAVGB/1.E3
                PXHTPC=XHAVGC/1.E3

                WRITE(12,500)TBULK,PCOPB,
     1 PXHTPB,TDELT,
     1 PXHTPC,TDELTC,PFOMB,PFOMC
  500 FORMAT(1X,F4.0,1X,F12.2,3X,
     1 F8.2,1X,F6.2,1X,F8.2,1X,F6.2,1X,2(F12.2,1X))


  600 CONTINUE
                 RETURN
                 END
```

```
C*************************************************************

                SUBROUTINE HTBOIL(XHB,QO,DT,G,F,S,
     1  CPL,VISCL,VISCV,TCONL,
     2  RELF,D,XLATHT,SURTEN,RHOL,RHOV,TBULK,X,XLEN,PSATB)

C               THIS SUBROUTINE CALCULATES THE FORCED CONVECTION
C               BOILING HEAT TRANSFER COEFFICIENT

C               CALCULATE HEAT FLUX, QO, FROM FIXED PARAMETERS:
C      FLOWRATE AND LATENT HEAT
      COMMON/SUBRT/XS,XF,XCPL,XVISCL,XVISCV,XTCONL,XRELF,
     2 XD,XXLATHT,XSURTEN,XRHOL,XRHOV,XTBULK,XX,XXLEN,
     3 XPSATB



                EXTERNAL Q
                XF=F
                XS=S
                XCPL=CPL
                XVISCL=VISCL
      XVISCV=VISCV
                XTCONL=TCONL
                XRELF=RELF
                XD=D
                XXLATHT=XLATHT
                XSURTEN=SURTEN
                XRHOL=RHOL
       XRHOV=RHOV
                XTBULK=TBULK
                XX=X
                XXLEN=XLEN
                XPSATB=PSATB
C CALCULATE THE UNIFORM HEAT FLUX REQ'D TO COMPLETELY
C VAPORIZE THE FLUID IN THE PIPE LENGTH,XLEN
  100           QO=G*XLATHT/(4.*XLEN/D)+(1.E-7*D*G**3)/(8.*XLEN)
     1 *((1./(RHOV**2))-(1./(RHOL**2)))

      TGUESS1=0.
                TGUESS2=100.
                EPSXA=0.01
                EPSXR=0.01
                EPSYA=0.01
                EPSYR=0.01
                MODE=2

C ROOTM FINDS THE DELTAT IN THE CHEN CORRELATION THAT
C  YIELDS THE CORRECT QO=HCALC*DELTAT
C AFTER ITERATION ON DELTAT, WE CALCULATE HEAT
C TRANSFER COEFFICIENT FROM QO/DELTAT
C DELTAT INITIALLY GUESSED BETWEEN 0&100 K

  200           CALL ROOTM(DELTAT,TGUESS1,TGUESS2,EPSXA,EPSXR,
     1   EPSYA,EPSYR,Q,QO,INDEX,MODE)
                DT=DELTAT
```

```
  300 XHB=QO/DELTAT
                RETURN
                END



C************************************************************
                SUBROUTINE DELTAP(X,D,G,L,DP,RHOL,RHOV,VISCL)
                REAL L
                EXTERNAL RINTPH
C CALCULATE TWO-PHASE PRESSURE DROP (REF COLLIER PAGE 37)



C               INTEGRATE PHLOTT FROM 0 TO X
C               USE V.ARP NUMERICAL ROUTINE FOR INTEGRATION
                XLWR=0.
  300           CALL INTGRL(PHIAVG,RINTPH,XLWR,X)
C               CALCULATE FFO(FRICTION FACTOR FOR TOTAL FLOW
C     CONSIDERED LIQUID)
  400 FFO=0.079/(G*D/VISCL)**0.25
C               CALCULATE TWO-PHASE FRICTION PRESS. DROP
  500           DPFTP=(2.*FFO*G**2*L/(D*RHOL))*(PHIAVG/X)
C
C               CALCULATE ACCELERATION PRESS. DROP
                DPATP=(G**2)*((1./RHOV)-(1./RHOL))
C               CALCULATE TOTAL TWO-PHASE PRESS. DROP
  700           DP=DPFTP+DPATP
                RETURN
                END
```

```
C*******************************************************

                FUNCTION Q(DELTAT)

C  THIS FUNCTION CALCULATES THE FORCED CONVECTION BOILING
C  HEAT TRANSFER COEFFICIENT USING THE CHEN CORRELATION


                COMMON/SUBRT/XS,XF,XCPL,XVISCL,XVISCV,XTCONL,XRELF,XD,
     1  XXLATHT,XSURTEN,XRHOL,XRHOV,XTBULK,XX,XXLEN,
                2  XPSATB



      COMMON/LSQ/COEF(2)
C CALCULATE SINGLE PHASE HTCOEFF BASED ON LIQUID ONLY
C   CALCULATE REYNOLDS NO AND PRANDTL NUMBER

  350           PRL=XCPL*XVISCL/XTCONL
  400           XHCL=0.023*(XRELF)**0.8*PRL**0.4*XTCONL/XD

C CALCULATE NUCLEATE POOL BOILING HT TRANS COEFF,XHNB

C               CALCULATE PROPERTIES PARAMETER

  550           XNUM=(XTCONL**0.79)*(XCPL**0.45)*(XRHOL**0.49)
  600           XDENOM=(XSURTEN**0.5)*(XVISCL**0.29)*(XXLATHT**
     1    0.24)*(XRHOV**0.24)
  650           PROPS=XNUM/XDENOM

C               CALCULATE DPSAT
C                               DPSAT IS PSAT AT TWALL - PSAT AT TBULK
C                               PSAT AT TBULK IS INPUT VAPOR PRESSURE DATA
C          NEED TO GET PSAT AT TWALL

C       CALCULATE TWALL

  700           TWALL=XTBULK+DELTAT

                PSATW=EXP(COEF(1)+COEF(2)/TWALL)

  800           DPSAT=PSATW-XPSATB
                IF(DPSAT.LT.1.)THEN
                 DPSAT=1.
                ELSE
                CONTINUE
                ENDIF
  820 IF(DELTAT.LE.0.)THEN
      XHNB=0.
                 ELSE
  850           XHNB=0.00122*PROPS*DELTAT**0.24*DPSAT**0.75
                ENDIF
  900           XHTPB=XHCL*XF+XHNB*XS
 1000           Q=XHTPB*DELTAT

                RETURN
```

```
                END

C*****************************************************


                FUNCTION RINTPH(XX)

C               THIS FUNCTION IS THE ALGORITHM FOR INTEGRATING THE
C               PRESSURE DROP CORRECTION FACTOR (PHLOTT)

                COMMON/SUBRT/XS,XF,XCPL,XVISCL,XVISCV,XTCONL,XRELF,XD,
     1  XXLATHT,XSURTEN,XRHOL,XRHOV,XTBULK,DUMMY,XXLEN,
                2  XPSATB



  200           IF(XX.EQ.0.)THEN
       PHLOTT=1.
                ELSEIF (XX.EQ.1.)THEN
       PHLOTT=0.
                ELSE
  250           AA=SQRT((XRHOV/XRHOL))
                BB=(XVISCL/XVISCV)
                BB=BB**0.1
                CC=(1.-XX)/XX
      CC=CC**0.9
                AAS=AA*AA
                BBS=BB*BB
                CCS=CC*CC

                 PHILTT=1.+(20./(CC*BB*AA))+(1./(CCS*AAS*BBS))
                 DXX=1.-XX
                 PHLOTT=(DXX**1.75)*PHILTT
  300           ENDIF
                RINTPH=PHLOTT

                RETURN
                END

C*****************************************************


                SUBROUTINE HTCOND(XHC,XTT)
                COMMON/SUBRT/XS,XF,XCPL,XVISCL,XVISCV,XTCONL,XRELF,XD,
     1  XXLATHT,XSURTEN,XRHOL,XRHOV,XTBULK,XX,XXLEN,
                2  XPSATB



C               THIS SUBROUTINE CALCULATES THE FORCED CONVECTION
C               CONDENSING HEAT TRANSFER COEFFICIENT INSIDE HORIZONTAL
C               TUBES (REF:BREBER,PALEN,TABOREK)
C               VALID FOR ANNULAR FLOW OR BUBBLE FLOW

C               CALCULATE LOCAL PHILTT-TWO PHASE PRESS DROP CORRECTION
C               PARAMETER USING CHISOLM CORRELATION
  100 PHILTT=1.+(20./XTT)+(1./XTT**2)
```

```
20 PRL=XCPL*XVISCL/XTCONL
30 XHC=0.023*(XTCONL/XD)*(XRELF**0.8)*PRL**0.4
  1 *(PHILTT)**0.45

              RETURN
              END
```

```
C*************************************************************

      SUBROUTINE LSQ2D(C)
      PARAMETER (NMAX=10)
      DIMENSION XX(NMAX), YY(NMAX), C(50)
                DIMENSION TBULK(4),RHOL(4),RHOV(4),VISCL(4),
     1 VISCV(4),CPL(4),CPV(4),TCONL(4),TCONV(4),
     2 SURTEN(4),XLATHT(4),PSATB(4)

      COMMON /FITT/ XFUN(50), YFUN, NFUN, NWRITE
                COMMON/DATA/TBULK,RHOL,RHOV,VISCL,VISCV,CPL,
     1 CPV,TCONL,TCONV,SURTEN,XLATHT,PSATB,
     2 D,XLEN,TCRIT,PCRIT,TBP

C  OUTPUT WILL BE ON TAPE20
      NWRITE=20
      OPEN (20, 'LSQ2D.COF')
C USE DATA READ FROM TAPE 6 AND 7
                NPTS=0
                DO 10 I=1,4
C  IF VAPOR PRESSURE IS LESS THAN 0.1KPa THEN OMIT THAT
C  POINT IN THE FIT (THIS MEANS WE DON'T HAVE DATA THERE
C  AND/OR VAPOR PRESSURE IS TOO LOW ANYWAY)
C
                IF(PSATB(I).LT.100.)THEN
                GO TO 10
                ELSE
                NPTS=NPTS+1
                XX(NPTS)=TBULK(I)
                YY(NPTS)=PSATB(I)
                ENDIF
   10           CONTINUE
                NPTS=NPTS+1
                XX(NPTS)=TBP
                YY(NPTS)=1.01E05
                NPTS=NPTS+1
                XX(NPTS)=TCRIT
                YY(NPTS)=PCRIT
                DO 40 N=1,NPTS
C  CALCULATE INDIVIDUAL TERMS
      CALL FGEN (XFUN, NFUN, XX(N))
C  WEIGHTS
      WT = 1.
      DO 30 K = 1, NFUN
   30 XFUN(K) = XFUN(K) * WT
      YFUN=ALOG(YY(N)) * WT
      CALL FIT
   40 CONTINUE
   50 CONTINUE
      JFUN=NFUN

      CALL COEFF
C  CONSTANTS MUST BE OBTAINED BEFORE CALLING STAT
      DO 60 I=1,JFUN
   60 C(I)=XFUN(I)
      CALL STAT
```

```
      DO 70 I=1, NPTS
         CALL FGEN(XFUN, NFUN, XX(I))
         YCALC=0.
         DO 65 J=1, NFUN
            YCALC=YCALC + XFUN(J)*C(J)
   65    CONTINUE
         YCALC=EXP(YCALC)
         YDIF=YY(I)-YCALC
         WRITE(20, 69) XX(I), YY(I), YCALC, YDIF
   70 CONTINUE
                CLOSE (20)
   69 FORMAT (4G14.5)
                RETURN

      END
C*******************************************
      SUBROUTINE FGEN(F, N, X)
      DIMENSION F(*)
C  N MUST NOT EXCEED 50 (WITH THIS VERSION OF FITTER)
      F(1)=1.
      F(2)=1./X
      N=2
      RETURN

                END
```

```
C*******************************************************
C*******************************************************
      SUBROUTINE INTGRL (ANSWER, FUNC, XMIN, XMAX)
C OUTPUT-------------------------------------------------
C     ANSWER = INTEGRAL OF FUNC FROM XMIN TO XMAX
C INPUT--------------------------------------------------
C     XMIN, XMAX
C VERSION MARCH 13 1986, VDA -------NEWTON-COTES 7TH ORDER INTEGRATION
C      IMPLICIT DOUBLE PRECISION (A-H, O-Z)
      DIMENSION C(8)
                 EXTERNAL FUNC
      DATA JMAX /8/
      DATA C /  751., 3577., 1323., 2989.,
     1         2989., 1323., 3577.,  751./
      H      = (XMAX - XMIN)/REAL (JMAX-1)
      ANSWER = 0.
      DO 10 J=1, JMAX
         X = XMIN + H*REAL(J-1)
         YVALUE = FUNC (X)
         ANSWER = ANSWER + C(J)*YVALUE
   10 CONTINUE
      ANSWER = ANSWER * (7.*H/17280.)
      RETURN
      END



                SUBROUTINE SIMPSON(FSUBI,STEP,ANS)
C  THIS SUBROUTINE INTEGRATES THE ARRAY CONTAINED IN FSUBI
C OVER THE INTERVAL DEFINED IN THE MAIN PROGRAM

                DIMENSION FSUBI(0:10)
C USE SIMPSON'S RULE TO FIND THE AVG VALUE FOR FSUBI
                ANS=(STEP/3.)*(FSUBI(0)+4.*(FSUBI(1)+FSUBI(3)
     1 +FSUBI(5)+FSUBI(7)+FSUBI(9))+2.*(FSUBI(2)
     2 +FSUBI(4)+FSUBI(6)+FSUBI(8)+FSUBI(10)))

                RETURN
                END
```

APPENDIX B. SUMMARY LIST OF COMPANIES CONTACTED

List of Companies Contacted by Telephone

1.
DOW CORNING HEAT TRANSFER FLUIDS
DEPT. A0021 BOX 0994
MIDLAND, MICHIGAN
48686-0994
PHONE 517-496-6000

2.
DOW CORNING
ADDRESS AS ABOVE

3.
MULTITHERM CORP.
125 S FRONT ST.
COLWYN, PA. 19023
1-800-225-7440

4.
GEORGE MANN AND CO.
DEPT 665
HARBORSIDE BLVD, PO BOX3066
PROVIDENCE,RI 02940
401-781-5600

5.
GENERAL ELECTRIC
SILICONE PRODUCTS DIV
SECTION TR84
WATERFORD,NY 12188
PHONE 518-233-2309

6.
3M INDUSTRIAL CHEMICAL PRODUCTS DIV
3M CENTER BLDG X 236-2B-01
ST. PAUL, MINN. 55144
PHONE:612-733-6282
PHONE:612-736-5242

7.
MONSANTO CHEMICAL CO.
800 N. LINDBERGH BLVD.
ST. LOUIS, MO
PHONE: 800-433-6997

8.
MAINSTREAM ENGINEERING CORP.
268 N BABCOCK ST
SUITE C
MELBOURN, FLORIDA
32935
PHONE:407-242-7003

9.
MOBIL OIL
150 E. 42ND ST
NEW YORK, NY
PHONE 1-800-662-4525

10.
SONNEBORN-WITCO
520 MADISON
NEW YORK, NY

11.
WALPEX TRADING CO.,INC
NEW YORK, NY
PHONE 212-921-8260

12.
MONTEDISON-AUSIMONT
44 WHIPPANY RD
MORRISTOWN,NEW JERSEY
07962
PHONE:201-292-6250

13.
SUPER-TROL DIV., ENERCON SYSTEMS INC
ELYRIA, OHIO

14.
EXXON
HOUSTON, TEXAS
PHONE:1-800-443-9966

15.
STAUFFER CHEM CO

16.
AKZO CHEMIE
CHICAGO,ILLINOIS
PHONE:312-906-7500

17.
PARK CHEMICAL CO
DETROIT, MICH
PHONE:313-895-7215

18.
EMERSON ELECTRIC CO
PITTSBURG, PA
PHONE:412-967-3800

19.
E. H. KELLOG
MT. VERNON, N.Y.
PHONE:914-664-3045

20.
UNION CARBIDE SILICONES
OLD RIDGEBURY ROAD
DANBURY, CONNECTICUT
PHONE:1-800-331-9275

21.
UNION CARBIDE
NEW YORK
PHONE:1-800-242-7226 OR 914-784-2278

22.
NORTON PETROLEUM CO.
290 POSSUM PARK RD.
NEWARK, DE
PHONE:302-731-8220

23.
PARATHERM CORP.
1050 COLWELL LANE, BLDG #2
CONSHOHOCKEN, PA 19428
PHONE:215 941-4900

24.
AMERICAN HYDROTHERM CO
MANHATTEN, NY
PHONE:212--889-7100

25.
KEMSTAR CORP
LOS ANGELES,CALIF.
PHONE:213-391-8510

26.
DUPONT-BLOOMINGTON
PHONE:302-774-1000

27.
AMETEC CORP
DELAWARE
PHONE:302-995-0560
DUPONT-BLOOMINGTON 302-774-1000

Foreign Companies Contacted by Correspondence

Soken Chem. & Engineering Co. Ltd
Japan

Hoechst UK Ltd.
Great Britain

Wacker-Chemie
Germany

Rhone-Poulenc Ltd
Great Britain

Burmah-Castrol Ltd.
Ireland

Bayer UK Ltd.
Great Britain

Petrofina UK Ltd.
Great Britain

Hercules Ltd.
Great Britain

Degussa Ltd.
Great Britain

Esso Petroleum Co.
Great Britain

Huls Nederland
The Netherlands

March 20, 1989

Hoechst UK Ltd.
Hoechst House
Salisbury Road
TW46JH Hounslow
Great Britain

Dear Sir or Madam:

I am currently associated with a research project for the U.S. National Aeronautics and Space Administration (NASA). We are searching for suitable heat transfer fluids that may be used on manned spacecraft. If your company is a supplier or manufacturer of heat transport media, would you please forward this letter of inquiry to the appropriate department.

The candidate heat transfer fluid (single component or azeotropic mixture) is to operate two-phase (boiling system) in a pumped-closed-loop thermal bus. Because of certain environmental constraints, the fluid thermodynamic properties must fall within certain limits.
Two other especially important requirements of the candidate fluid are that it must be nontoxic and nonflammable. A list of the requirements are:

(1) Freezing point less than $0^{o}C$.
(2) Vapor pressure at ambient temperature (approximately $20^{o}C$ greater than 1 atm.
(3) Critical temperature greater than about $50^{o}C$.
(4) Flash point greater than $205^{o}C$, fire point greater than $230^{o}C$.
(5) Nontoxic and will not decompose into toxic substance(s) when subjected to high temperature, about $300^{o}C$. This is not an operating temperature; this temperature may be encountered in a failure condition on the surface of a catalytic converter.

If your company can supply a fluid meeting the above requirements, would you please send us a letter or brochure containing the fluid's technical data, pricing and availability. We would also be interested in fluids approximately meeting the requirements.

Companies Specializing in CFC Production Contacted by Correspondence

Hoechst Aktiengesellschaft
Germany

Asahi Glass Co. Ltd.
Japan

Showa Denko KK. Ltd
Japan

E. I. du Pont de Nemours Co.
USA

Allied Signal Corp
USA

Essex Chemical Corp./Racon Inc.
USA

Pennwalt Corp.
USA

Akzo Chemical BV
The Netherlands

Daikin Industries Ltd.
Japan

Kali Chemie Aktiengesellschaft
Germany

Atochem SA
France

March 27, 1989

Hoechst Aktiengesellschaft
Brueningstr. 38
Frankfurt, Hessen 6230
West Germany

Dear Sir or Madam:

The National Institue of Standards and Technology is currently associated with a research project for the U.S. National Aeronautics and Space Administration (NASA). We are searching for suitable heat transfer fluids that may be used on manned spacecraft.

The candidate heat transfer fluid (single component or azeotropic mixture) is to operate two-phase (boiling system) in a pumped-closed-loop thermal bus. Because of certain environmental constraints, the fluid thermodynamic properties must fall within certain limits.
Two other especially important requirements of the candidate fluid are that it must be nontoxic and nonflammable. A list of the requirements are:

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(3) Critical temperature greater than about $50^{o}C$.
(4) Flash point greater than $205^{o}C$, fire point greater than $230^{o}C$.
(5) Nontoxic and will not decompose into toxic substance(s) when subjected to high temperature, about $300^{o}C$. This is not an operating temperature; this temperature may be encountered in a failure condition on the surface of a catalytic converter.

We are aware of your company's production of chlorofluorocarbons which except for item (5) above might be a suitable candidate. Therefore, we would like to know if you can supply any alternative fluids which might be considered for this application. Please provide any relevant technical information that you have available for our consideration. A telephone call or letter from your technical or marketing department, if you require further information, would be welcome.

Contract T-4528P
Lyndon B. Johnson Space Center

NONTOXIC HEAT TRANSPORT FLUIDS FOR SPACECRAFT TWO-PHASE THERMAL CONTROL SYSTEMS

Final Report

September 30, 1989

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AUTHOR(S)

Patricia J. Giarratano, James F. Welch

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Lyndon B. Johnson Space Center
Houston, TX 77058

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[ ] DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

This report summarizes an investigation to determine the availability of a nontoxic, nonflammable, noncorrosive and thermally stable heat transport fluid suitable for two-phase thermal control systems in manned spacecraft. Approximately 860 chemical substances were sorted and ranked according to parameters that were defined and calculated to quantitatively evaluate fluids for the proposed application. A methodology was developed for the evaluation and ranking. A survey of world suppliers of heat transport fluids was also conducted to determine whether a suitable fluid is available. The investigation did not identify a fluid that can meet all the environmental and thermal property requirements required for safe and efficient performance in the spacecraft application.

KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

commercial heat transport fluids; heat transport; nontoxic fluids; spacecraft; thermal control; two-phase

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