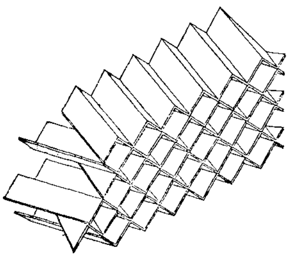

Fig. 2 PCM chamber fins.

Reference 1 showed the normal paraffins to have adequate heats of fusion and melt temperatures in the range of interest. In addition, the paraffins are compatable with aluminum and contract upon freezing. Two paraffins were particularly promising; Tridecane and Dodecane. Their properties are tabulated in Table 1.

Preliminary analysis of the two paraffins showed that Tridecane provided a greater radiator/capacitor combined heat rejection capability for the Airlock coolant loop, primarily due to the phase change temperature being near the required 28.8°F suit cooling module inlet temperature. Studies showed the need for a heat storage capability of 1200 BTU, requiring approximately 20 lb of Tridecane. From a detailed thermal analysis considering the PCM-to-fins-to-coldplate conductance, it was shown that a 1 in. thick PCM chamber achieved adequate conduction heat transfer to meet these requirements and provide an ullage space for expansion of the PCM.

Capacitor Prototype Tests

Two types of tests were conducted. The first test objective was to develop a thermal model. The capacitor inlet temperature was varied from +40°F to −15°F and back to 40°F at a constant flow rate of coolant.

Heat-transfer coefficients from the fluid to the coldplate faceplate were calculated using available coldplate data. An effective conductance of wax was found by calculating a conductance from the faceplate through the aluminum matrix core fin in series with a conductance from the fin into the wax. When the thermal model was run, the results did not agree with test data. At first, it was thought that the simplified conduction model was in error, but after trying other effective conductances, the data still could not be correlated. Finally, by changing the melt and transition temperatures to 20.5°F and 0.0°F, respectively, the correlation was excellent.

In the second test, the thermal capacitor inlet temperature and flow rate profiles were made to correspond to conditions that the thermal capacitor would encounter during a normal orbit. The inlet temperatures were varied from 36°F to −13°F while the coolant flow rate was varied. Figure 3 shows the capacitor inlet and outlet temperatures measured and the thermal model predicted outlet temperature for the prototype tests.

Radiator/Capacitor Performance Predictions

The test-correlated thermal model of the thermal capacitor was incorporated into the Airlock radiator coolant loop thermal model with the results shown in Fig. 1, showing that the original suit cooling design conditions can be met and even exceeded.

Table 1 Candidate paraffin phase change properties

	Tridecane	*Dodecane*
Melting temperature	22.3°F	14.7°F
Heat of fusion	65.4 BTU/LBM	93.0 BTU/LBM
Structural transition temperature	−0.6°F	—
Heat of transition	17.9 BTU/LBM	—

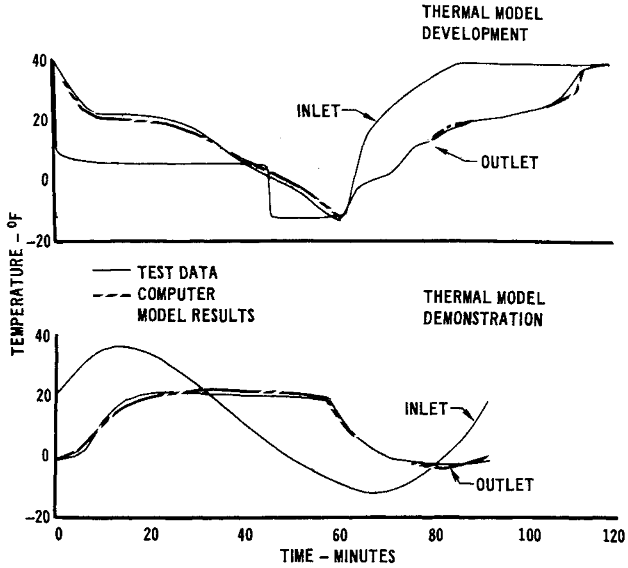

Fig. 3 Capacitor prototype test results.

Conclusions

The Airlock thermal capacitor development has demonstrated the feasibility of a new concept in the application of phase-change materials to the temperature control of an Earth orbiting vehicle. As a result of the averaging effect of the thermal capacitor, the radiator performance in terms of potential for heat rejection was increased for the same radiator area. The thermal capacitor was not optimized with respect to usual design parameters, but conservative estimates were made and tried in the interest of limiting time spent in the development.

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Thermal Control of a Jovian Survivable Probe

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Introduction

A STUDY was conducted to determine the technical feasibility of a 1978 atmospheric probe mission to Jupiter.[1] A part of that study was an evaluation of thermal protection

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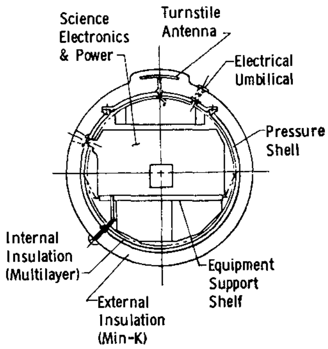


Fig. 1 Typical descent probe arrangement.

problems, particularly as they vary with increasing depth of atmospheric penetration. Probe survival to a pressure of 1000 bars, where the corresponding atmospheric temperature is nominally 1150°C and the composition is a H_2/He mixture, was examined. Although the study included all major aspects of the mission, this discussion treats only the thermal control requirements of the planetary atmospheric descent phase. Planetary entry is accomplished with an aeroshell/heat shield, which is separated after entry. Details regarding the study ground rules, scope, other results, etc. can be obtained from Carrol's paper.[2] The significant parameters affecting the thermal control design included the atmospheric models (environment) and the descent profiles (exposure to that environment). The probe payload consisted of the science, power, data, and telecommunication subsystems. The temperature requirements (operating) varied from component to component but were averaged as 4 to 52°C. Figure 1 shows the general arrangement of a typical descent probe.

Thermal Control Approach

The thermal design of the probe was dictated by the descent phase, which begins above the suspected cloud region at a pressure of 0.1 millibars and a temperature of −160°C. The heat transfer is dominated so strongly by convection from the atmosphere that radiation can be neglected. The basic thermal control approach was to introduce a lag in the thermal pulse since the descent phase was short. Secondly, additional thermal capacitance was built into the probe to absorb energy dissipated by the equipment and energy entering through heat shorts. The thermal lag was provided by insulation and the capacitance was provided by phase change material (PCM). Because the problem is a transient one and because heavy pressure vessels are involved, the structural and thermal control requirements were analyzed together. How the structural material properties varied with temperature was an important consideration because it introduced an additional variable—selection of the material. In the more general case, the requirement is to control the temperature of a specific structural design. In this case, however, the minimum thermal-structural weight required different structural materials at different descent depths. The thermal control weights and volumes affected the structural weights and volumes, and vice versa.

Analytical Method

All of the thermal analyses was done with MITAS, a thermal analyzer computer program. The transient thermal model was utilized by assuming PCM weights and insulation thicknesses, limiting the payload temperatures to a maximum and controlling the shell temperature to a specified level, and optimizing the thermal-structural weight (the sum of the shell, internal structure, PCM, and insulation). A critical assumption was that the probe internal temperature at the beginning of the descent was 10°C.

Atmospheric thermophysical properties

Since the atmospheric models are gaseous mixtures, the properties of the constituents must be combined to obtain the properties of the mixtures. Trace constituents were ignored and the nominal model was assumed to be 75% H^2 and 25% He by weight. Properties for hydrogen and helium were obtained for most of the pressure and temperature range, although some of the data had to be extrapolated to the higher pressures. The specific heat was calculated on the basis of a weighted average, the viscosity was calculated with Wilke's equation, and the thermal conductivity was calculated using Brokaw's rule for mixtures of nonpolar gases.

Convection heat-transfer coefficients

During descent the heat-transfer coefficients are so high that the probe's surface temperature only lags the local atmospheric temperature by a few degrees. The correlation used for predicting the coefficient was $h = (k/OD)\,(2.0 + 0.16\,Re^{1/2}\,Pr^{1/3})$, where h = convection heat-transfer coefficient, k = atmospheric thermal conductivity, and OD = probe outer diameter. This equation is for forced convection over a sphere submerged in an infinite fluid.[3]

Phase change material characterization

The PCM was incorporated in the thermal model as a separate node, and its thermal characteristics were controlled by a special subroutine. The significant properties assumed for the PCM were heat of fusion = 63 cal/g and density = 1.52 g/cc. These properties are representative of available materials (e.g., the Trans-Temp series) and should be realizable through proper design.

Insulation characterization

Two types of insulation were used in the various probe configurations—multilayer, which requires a vacuum for efficient operation, and Min-K 2000, used for applications that involve exposure to the atmosphere. Representative property values for the multilayer insulation were density = 96 kgs/m³ and conductivity = 0.0007 w/m/°K (penetrations are accounted for separately). Although the mean multilayer temperatures vary from −60 to 315°C, it was felt that the selected conductivity was adequate for this range and was not varied with temperature.

For the exposed insulation, Min-K 2000 was selected as the best available material, based on the limited information on hand. The only test data available included the effects of temperature but not pressure. Because of the nature of the material and of the atmosphere, the conductivity was assumed to be the sum of the vacuum conductivity of the Min-K and the conductivity of the atmospheric gas as a function of pressure and local temperature (at the location of the conductor). The resultant conductivities are very much higher than for multilayer.

To illustrate the sensitivity of the probe weight to the Min-K conductivity assumed, a comparison was run for a typical probe mission, first with the available conductivity data and then with the technique previously described. The configuration was a spherical titanium shell covered with Min-K. Using the test data, the probe required an insulation thickness of 8.26 cm, compared to 14.92 cm based on the above assumptions.

Pressure shell calculations

As mentioned, the thermal analysis of the descent probes was optimized by selecting the design with the lowest thermal-structural weight as long as it also satisfied the temperature requirements. Since the pressure shell weight was a major fraction of this total, it had to be accurately predicted. The weights were estimated by one of two methods, depending on the combination of design pressure, shell temperature, and material. In both methods the interior volume of the probe was calculated by defining a payload weight and assuming a packaging density (640 kgs/m^3). Then the inner radius of the shell envelope was calculated from this volume (assuming a sphere) and the assumed multilayer insulation thickness. For example, if titanium at 50°C were assumed, at design pressures below 250 bars buckling criteria were used and the shell thickness was calculated as a function of Poisson's ratio, the modulus of elasticity, the design pressure, and the safety factor. To account for the weight added by closures and penetrations, the bare weight was increased by a factor that is a function of the design pressure. For the same example at design pressures above 250 bars, thick-wall criteria were used. The inner radius was calculated as before and the outer radius was calculated as a function of the yield stress, design pressure, and safety factor. The shell weight was then computed from these two radii with the same allowance for closures and penetrations.

Penetrations

In a configuration using multilayer insulation, penetration heat leaks represent the main source of energy transfer into the probe from the atmosphere. With external insulation, penetration heat leaks are significant although much smaller than those through the insulation itself. Penetrations result from sampling ports and sensor leads in the science subsystem, and from electrical leads in the power and telecommunication subsystems. A typical value for the sum of these penetrations is 0.019 watts/m/°K. Additional penetrations result from structural supports from the pressure shell to the equipment shelf and supports from the external insulation cover to the pressure shell.

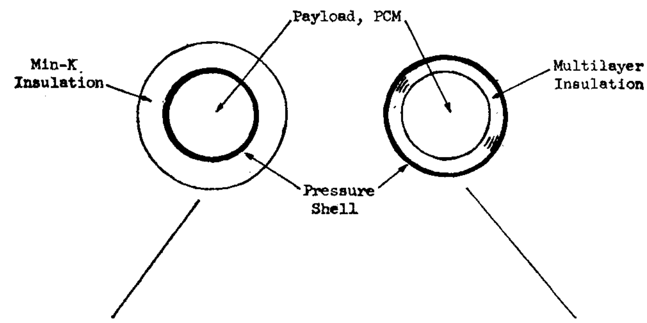
Configuration Tradeoffs

Pressure shells

The majority of the tradeoff study was performed on the "conventional" planetary descent probe designs, i.e., spherical pressure shells with insulation. One result of the study described in Ref. 1 was that a split probe concept was required if the descent depth was 1000 bars. A split probe concept utilizes two probes—a lower probe that descends to the design depth and transmits to an upper probe that remains in the upper atmosphere and acts as a relay. This split probe concept is more favorable than a single probe because the very high signal attenuation in the dense atmosphere would force the transmitter to be very large if the signal was required to reach the flyby spacecraft. The weight comparisons were conducted on the basis of total probe weights rather than thermal-structural weights. This included the payload, an insulation cover, and the required fins and parachute, some of which are size-dependent.

Upper probe

The upper probe tradeoff was performed at a depth of about 45 bars and 290°C and evaluated two configurations—an aluminum shell covered by Min-K and a titanium shell containing multilayer. The ballistic coefficient was 0.04 kgs/m^2, the descent time was 2.57 hr, and the power dissipation was 99.3 w. The comparisons (Fig. 2) show a decided weight and size advantage for the exposed shell. Previous studies of Venusian entry probes[4,5] have shown the external insulation approach to be weight-advantageous, but in the Jovian atmosphere the expected Min-K performance is so degraded that its weight is high and not offset by the shell weight savings, partially because of the additional volume required by PCM. Also, the *OD* of the exposed shell design is smaller, which allows a more compact aeroshell.



Aluminum		Titanium
25.5	Payload (kgs)	25.5
4./46.5	Pressure Shell Wt/Dia (kgs/cm)	5.5/46.2
7.8	Support Structure (kgs)	3.8
2.3	Aerodynamic System (kgs)	1.4
11.2/4.3	Min-K Insul Wt/Thickness (kgs/cm)	
	Multilayer Insul Wt/Thickness (kgs/cm)	0.4/0.8
9.1	PCM (kgs)	0.9
59.8	Total Weight (kgs)	37.3
55.1	Total Diameter (cm)	46.2

Fig. 2 Configuration tradeoffs, upper probe.

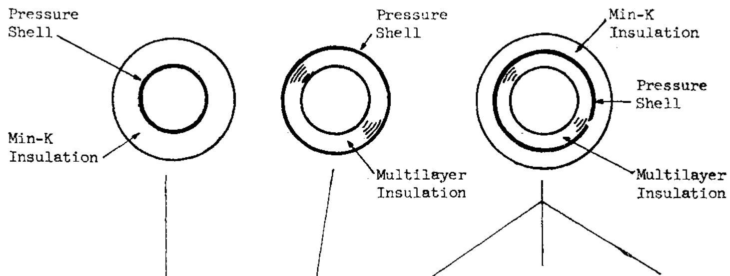
Lower probe

The tradeoff for the lower probe was performed at a depth of 1000 bars and 1150°C, and considered a third configuration as well as those described above. The third configuration had Min-K outside the shell and multilayer inside, and was evaluated with three different shell materials. It was necessary to use titanium for the protected shell and columbium B-66 for the exposed shell at the higher temperatures. For shells with insulation inboard and outboard, it was a matter of selecting a design temperature at which the mechanical properties were optimized. Inconel and René were selected because of their high strength, and beryllium was selected because of its high heat capacity. The descent profile had ballistic coefficients of 2.95, 1.29, and 2.95 kgs/m^2, the time was 2.57 hr, and the power dissipation was 32.5 w. The comparisons are shown in Fig. 3 and include a large range of weights and sizes. The largest variable is the shell weight. The minimum weight configuration is the Inconel 718 design although the René 41 design is smaller because of the lower Min-K thickness.

The results of these tradeoffs were used to select the configurations in all of the subsequent mission studies. For brevity, the configurations are referred to by designating the shell material and insulation type, e.g., Min-K/Inconel/multilayer.

Alternative configurations

Several other thermal-structural configurations could be considered if any of the science, power, or telecommunication equipment could be designed to withstand the atmospheric pressure or, even better, both the atmospheric pressure and temperature. The objective is to eliminate the requirement for the heavy pressure shell and reduce the problem of high-pressure, high-temperature seals. These configurations are as follows: 1) an equipment compartment that is vented to the atmosphere and the incoming atmospheric gas is cooled by a phase-change heat exchanger; 2) a closed system where the



	Titanium	Columbium	Rene at 815°C	Inconel at 595°C	Beryllium at 540°C
Payload	15.3	15.3	15.3	15.3	15.3
Pressure Shell Wt/Dia	30.5/41	354.7/53	56.2/40	39./39	82.1/51
Support Structure	12.2	3.2	5.9	6.8	6.8
Aerodynamic System	7.7	8.6	3.6	4.1	5.0
Min-K Wt/Thickness	48.1/15		6.4/3.3	14.5/6.9	4.1/1.5
Multilayer Wt/Thickness		1.8/4	0.5/1.0	0.5/0.8	0.5/0.6
PCM	13.6	5.0	1.4	0.9	0.9
Total Weight (kgs)	126.	389.	89.	81.	115.
Total Diameter (cm)	71.	53.	47.	53.	54.

Fig. 3 Configuration tradeoffs, lower probe.

atmospheric pressure is transmitted through a bellows to a contained fluid, possibly PCM; 3) a probe that carries along a gas, stored at high pressure, that is vented inside the probe at a rate matching the atmospheric pressure increase; and 4) a probe that is internally pressurized to a level at which the shell thickness is minimized, considering the tension loads when there is no atmosphere and the compression loads when there is. All of these configurations become more competitive with the pressure shell concept as the design pressure increases. Therefore, these concepts were preliminarily examined for the 1000 bar depth. The reference design was selected as the Min-K/Inconel/multilayer probe from Fig. 3.

The capability of the components to withstand these high pressures is speculative. A small feasibility test Martin Marietta conducted to explore this possibility demonstrated that several representative electronic components apparently can operate at 1000 bars. Based on these results and assuming 1975 state-of-the-art, the pressure capability of each of the probe components was assessed (yes or no). On a weight basis, about 40% of the components were assumed to require protection from the pressure above 1 to 2 bars.

With this as a ground rule, comparative weights for concept 4 were approximated. The internal pressure used was 415 bars and the total probe weight was 125 kgs, compared to 81 kgs for the reference design. Because none of the other concepts appeared to be weight-competitive, a fifth alternative design was evaluated. A small pressure vessel was used for the components requiring protection and the other components were potted with PCM and covered with Min-K. The probe weight for this configuration was 99 kgs.

Parametric studies

Probe weight vs depth

To determine how descent probe weight varied with depth, two descent times were selected, and ballistic coefficients were then assumed that would yield a range of convenient depths for that descent time. The payload was parameterized on the basis of transmitter size, which affected both the weight and the power dissipation. The transmitter sizes selected from the earlier mission studies were 20, 40, and 2.5 w, the latter corresponding to a relay probe. The configuration types were selected and then analyzed to optimize the thermal-structural weights. Figure 4 shows this relationship for a 2.5 hr descent time, and the final report[1] also shows a plot for a 3.5 hr descent. The pressure vessel material and the insulation configuration vary from probe to probe.

Probe weight vs time for 1000 bars

Four ballistic coefficients were selected to analyze how the descent probe weight varied as a function of the time required to reach a depth of 1000 bars. A single payload (a 2.5 w transmitter split probe) and a single configuration (Min-K/René/multilayer) were used. The results indicate that the descent probe weight is not as sensitive to descent time as it is to descent depth.

Single vs split probes

The split probe concept was evaluated against single probes for several parameters. A plot[1] of probe weight vs pressure corresponding to a radius of periapsis (R_p) = 2.0 and entry angle (γ_E) = −20° shows that split probes are lighter for pressures above 225 bars.

Probe weight vs periapsis radius

The entry and descent geometries greatly affect optimization of the data return from the descent probe(s). With the flyby spacecraft acting as a relay, such factors as range, probe antenna aspect angle, and spacecraft antenna look angle become critical in shaping the trajectories. Other variables that can be changed to overcome the range and attenuation losses are the transmitter power, frequency, data rate, antenna

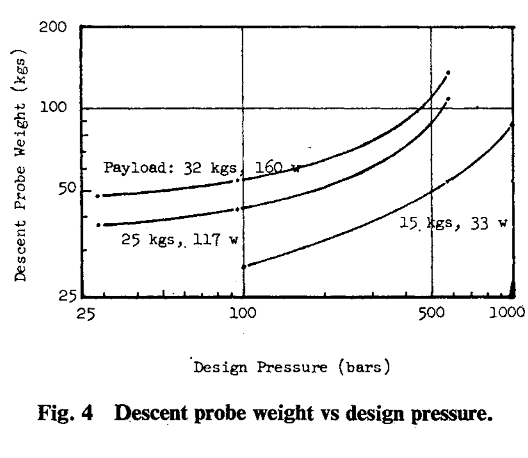


Fig. 4 Descent probe weight vs design pressure.

size, and signal acquisition capability. Given certain constraints on all these variables, probe weights were evaluated as a function of R_p (the closest approach of the spacecraft to the planet). This relationship is shown in the final report[1] for the case of a single probe, $\gamma_E = -20°$, $P = 50$ bars, and shows that as R_p increases the probe weight increases. The range (and signal loss) also increases and thus a larger transmitter is required, causing increases in the thermal-structural weight.

Probe weight vs entry angle

Another aspect of the communications geometry is γ_E, which affects both range and probe aspect angle. However, the power requirements did not prove to be a significant factor in the probe weight and in fact the transmitter size decreased at the steeper entry angle for the 300 bar design because of the shorter range at the end of the mission. The probe weights are shown in the final report,[1] with design pressure as a parameter.

The probe's thermal design is affected by entry angle variation through the resultant variation in the structural supports carrying the entry loads from the aeroshell to the probe's internal equipment. As the entry angle increases, the cross-sectional area of the supports increases and therefore the heat transfer into the probe (during descent) increases. These supports represent the major heat leak into the probe through the multilayer insulation. They are designed to minimize heat conduction by making them out of titanium and installing them at 30°, which doubles their conduction path. The impact of entry angle on the thermal design, however, is overshadowed by the very large weight increases in the aeroshell and heat shield, due to the higher dynamic pressures and heating rates.

Conclusions

The thermal control objective in this study was to determine the system penalties resulting from thermal protection requirements of probes descending as deep as 1000 bars. The configuration tradeoff study showed that the relatively low pressure and temperature environment favored the exposed pressure shell with multilayer insulation, and the relatively high pressure and temperature environment favored the use of both external and internal insulation with a pressure shell. In the former case, it means a strong dependence on seals, the possibility of thermal stresses in the shell, and an inefficient application for multilayer. In the latter case the performance of the exposed insulation is critical not only to the payload temperature but to the shell where high temperatures mean lower mechanical properties and an accentuated high pressure seal problem. Until it is demonstrated that payload components are compatible with high pressures, little gain can be expected from the alternative configuration designs. There is a strong need for performance data on insulations in these applications and environments before realistic thermal-structural designs can be postulated for Jovian atmospheric probes.

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Subsonic, Transonic, and Supersonic Nozzle Flow by the Inverse Technique

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Nomenclature

A,B,C = centerline velocity constants
a = acoustic velocity
b = stretching function constant
c_p = specific heat, constant pressure
C_D = nozzle mass flow coefficient
F = isentropic constant
H = enthalpy
P = pressure
q = Velocity vector
r,θ,z = cylindrical coordinates
T = temperature
u,v,w = cylindrical velocities
γ = specific heat ratio
ε_c = contraction ratio
ξ = axial stretched coordinate
ρ = density
ψ = streamline, stream function

Subscripts and Superscripts

o = stagnation condition
t = throat
cl = centerline
$*$ = sonic value
$1\text{-}D$ = one dimensional

Introduction

TWO-dimensional calculations for nozzles and wind tunnel have usually been treated in three distinct regimes: the subsonic, the transonic, and the supersonic. Since we have a powerful tool for the solution of hyperbolic equations in the Method of Characteristics (MOC), the supersonic flow has received a great deal of attention. Flow solutions by MOC are initiated in the transonic region from an initial data surface which is a Cauchy boundary condition. At first, MOC calculations employed one-dimensional results for this initial data. However, special transonic analyses have now been derived reflecting to some degree the two-dimensional effects at the throat.[1–4] The subsonic flow which leads up to the throat has been largely ignored due to the difficulty of treating the elliptic problem. The classical method of solution of elliptic equations requires boundary conditions of the Neumann or Dirichlet type over a closed region. The solution for the interior points is effected by relaxation allowing the prescribed boundary conditions to determine the interior values. In gasdynamic flows, often these boundary conditions are not known; in fact, these conditions are often the primary purpose of the analysis. This is especially true of the transonic region boundary conditions which are useful for MOC supersonic flow solutions. Thus, it is difficult to treat each flow regime separately and the flow in a mixed region must be solved.

At the present time there are three methods for handling these flows: the Asymptotic Time Method, the Error minimization Technique, and the Inverse Cauchy Technique. The first makes use of the unsteady flow equations which are hyperbolic with respect to time.[5] This method has been shown feasible for flows initiated from an infinite reservoir where the initial velocities are zero. However, for flows originating

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