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Design of a Resistojet for Space Station Freedom

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ABSTRACT

In the mid 1990s, NASA will begin assembly of Space Station Freedom, a permanent outpost in a low-earth orbit. For the station to remain in that orbit, an altitude control system must be developed to resist the effects of atmospheric drag. One system being considered by NASA is called a resistojet and uses highly pressurized waste gases heated by electrical resistance to provide thrust on the order of 1 Newton. An additional function of the resistojet is to vent waste gases used by the station and its inhabitants. This report focuses on resolving the issues of system performance, flow and heater control, and materials selection and designing test procedures to resolve, by experimentation, any remaining issues.

The conceptual model of the resistojet consists of a shell wrapped by a resistive coil with gases flowing internally through the tube with ~~addition~~ additional components such as regulators, transducers, and thermocouples. For system performance, the major parameters were calculated from the desired thrust range, the pressure within the resistojet, and the cold flow mode of operation; waste gases were analyzed at 100% capacity and between 68.95kPa and 552 kPa. The design team found that any ventilation under all conditions would produce thrust, and therefore, it was decided to limit the design of the ventilation function. The design team proceeded with a simplified model to determine the nozzle throat diameter and chamber diameter.

The controller design for the resistojet system is unique in that it uses a "trial-and-error" process to control and maintain the performance of the resistojet system. The use of the MRAC (Model Reference Adaptive Control) system has already proven itself in the attitude control of the Exosat satellite. The MRAC system easily adapts to unknown variables, allowing it to obtain correct impulses while the composition of the waste gases varies over time.

A systematic procedure was used to conduct the materials selection for the resistojet, and the materials were optimized for environmental resistance and cost. The corrosion resistence of Molybdenum disilicide (MoSi$_2$), an electrical heating alloy, was singled out as the only element resistant at high temperatures to all of the waste gases because of its "self-healing" properties. Eventually however, plantinium was selected for the heating element of the coil, while MoSi$_2$ remained the selected material for the other components. An addition of 10% ceramics is ~~reqiured~~ required to control the brittle behavior of MoSi$_2$ for industrial application. In the overall consideration of the design, the cost and manufacturing issues of a MoSi$_2$ heating element was judged to be impractical and non-cost effective. The final coil design consists of a platinum wire with MgO insulation and a MoSi$_2$ sheath for corrosion resistance. The selection of MoSi$_2$ and ceramics in place of platinium parts (except for the coil) results in a estimated cost savings of 98% in materials and greater resistance against corrosion. The design team also chose to incorporate Inconel 600 for the plume shield and the casing because of its excellent properties for applications in space.and superior corrision resistant properties. The materials selection of the resistojet components optimizes the design for waste gas ventilation.

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BACKGROUND

When Space Station Freedom is finally launched into orbit and assembled, it is expected to remain in orbit for a duration of 30 years. There is a problem, however, with keeping the station at its designated altitude due to the fact that it is in a micro-gravity, as opposed to zero-gravity, environment. A small amount of drag acts on objects residing in low-earth orbit, inevitably pulling them in towards the earth if no equal and opposite force is applied. NASA has put considerable time and effort into the research and development of a system to maintain and control the altitude of Freedom. Spending cuts to NASA's budget has deemed it necessary to find a low cost system with the most efficient use of consumables.

One such system makes use of a *resistojet* to provide small amounts of thrust to the station over relatively long periods of time. The resistojet uses waste gases being discharged by other systems on the station as propellant which it heats by electric resistance to provide additional impulse. To decide whether this system will meet the needs of the space station, issues concerning system performance, flow and heater control, and materials selection must be resolved.

CLARIFICATION OF PROBLEM

The basic design for a resistojet already exists; the problem lies in tailoring it to meet the specific needs of the space station and use the available resources. The resistojet must not only perform the function of providing impulse for altitude control, but it must also vent all of the waste gases that accumulate onboard the station. The systems controlling the heater and the gas flow rate ~~rate of flow of the gases~~ must maximize the amount of gas being vented while providing the desired impulse. Interaction of the gases with each other and variability of the composition from cycle to cycle must also be considered.

Materials conventional to resistojet design may not meet the requirements for temperature range or the environment of space and will need to be selected carefully. Also requiring appropriate selection is the electric resistance heating element that will be used to heat the gases for calculated expansion. The placement of the heater within the chamber, the size and shape of the nozzle, and the shielding of exhaust plumes are additional problems that will need to be resolved. Procedures for testing resistojet performance must be developed and test apparatus designed in order to help resolve issues unable to be solved by analytical means. A specification sheet in Appendix A clarifies the constraints and functional requirements for the resistojet.

SPECIFICATIONS

The majority of the specifications listed in Appendix A are self-explanatory and do not require justification; however, the design team felt that the requirements crucial to embodiment are deserving of some degree of justification.

The chamber, heating element, and nozzle will be exposed to variable compositions of the five waste gases being considered. Non-corrosive, non-oxidizing materials must be selected, particularly for the heating element, the performance of which could be severely affected by oxidation due to gases such as CO_2 and water vapor.

Considering the issue of safety, it was decided to include in the design an emergency shut-off system powered by an independent source should the resistojet encounter a problem such as over-heating, over-pressurization, or fire within the chamber. To determine if any of these conditions exist, diagnostic capability would also need to be included in the design; however, the main function of a diagnostic system would be to aid crewmembers and ground controllers in determining when and what maintenance may be necessary.

FUNCTION DESCRIPTION

As mentioned previously, the resistojet must perform the two primary functions of providing impulse for altitude control and venting the maximum amount of waste gases possible.

The process by which it will accomplish these begins with the flow of waste gases from a storage tank to the resistojet chamber (See Figure 1). The high pressure at which the gases leave the tank requires that the gases pass through a regulator which must bring the pressure down to a value appropriate for passing through the chamber. Once inside the chamber, the gases are heated by electric resistance, accelerated by a converging-diverging nozzle, and expelled through the nozzle exit; thus providing impulse, a function of thrust over time, and venting waste gases simultaneously.

Temperature and flow rate control require the placement of temperature and pressure transducers at specific points along the jet, such as at the entrance to the chamber and the entrance to the nozzle. The thrust must also be monitored for control and diagnostic purposes. Appendix B displays the resistojet process in the form of a function structure.

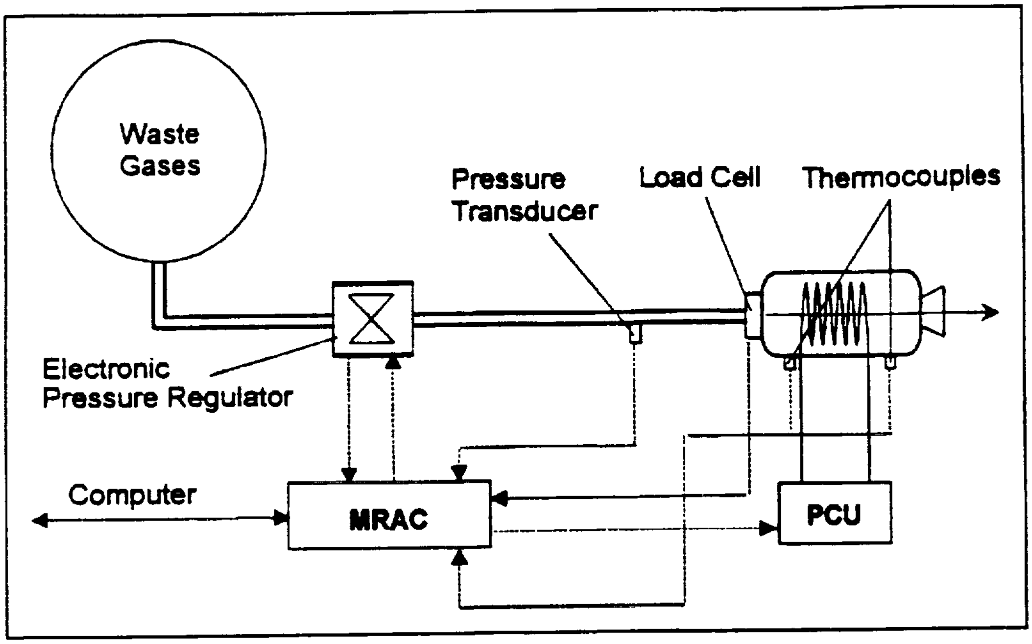


Figure 1. Resistojet process. Waste gases pass through the pressure regulator flow into the resistojet chamber where they are heated and released through a nozzle.

SOLUTION VARIANTS

A comprehensive list of solution variants for each of the sub-functions described in the previous section is shown in Appendix C. For the sub-function concerning flow regulation, the use of a simple orifice was ruled out because it does not allow for variable pressure. The remaining options were a mechanical and an electronic pressure regulator. The mechanical regulator was eliminated because it is less accurate than the electronic regulator and requires an additional electronic system to control it.

For heating of the gases, the only alternative solution to be eliminated during the initial evaluation was that of a parallel heating mesh through which the gases would flow. It was removed as an option because impurities in the gas mixture might clog up the mesh and block the flow.

The use of a manometer for monitoring the pressure of the gases was eliminated as a possible solution due to incompatibility with the micro-gravity environment. For measuring the gas temperature, the thermister and resistance temperature device (RTD) were eliminated because of accuracy degradation at temperatures exceeding 800°C. The use of a thermometer is impractical and would not be able to be easily read. For monitoring resistojet thrust, analytical means was ruled out as a solution because of lack of accuracy and the fact that it depends upon the values determined by the pressure sensors. If the pressure sensor fails or gives inaccurate readings, the true thrust cannot be determined. Additionally, variation of gas composition makes analytical determination of the thrust impractical.

Finally, for analysis and control of the parameters, the proportional (P), proportional plus derivative (PD), and proportional plus integral plus derivative (PID) controllers were all immediately eliminated because of incompatibility with the system. The proportional plus integral controller (PI) requires too much information about the system and was therefore deemed impractical.

CONCEPT VARIANTS

For all of the sub-functions except that of heating the gases, only one solution remains for each; an electronic pressure regulator for flow regulation, a pressure transducer, a thermocouple for measuring temperature, a load cell for measuring thrust, and a model reference adaptive controller (MRAC) for analysis and control. It is only the type of resistive heater which changes from variant to variant.

The heater solutions consist primarily of existing methods of resistive heating within a chamber or variants of these. They consist of the following and are shown graphically in Appendix D:

(1) Heated cylindrical shell with internal and external flow

(2) Finned coils with flow running perpendicular to the coil columns

(3) Internal coil with parallel, external flow

(4) Heated spheres packed together with flow traveling in between

(5) Heated cylindrical rods with flow perpendicular to the rods

(6) Cylindrical heater spanning circumference of chamber with internal flow

Evaluation

To evaluate the six concept variants in a thorough and unbiased manner, weighting criteria were developed and assigned weighting factors according to their importance in satisfying the function. Criteria and weighting factors were assigned as follows:

1) Reliability	.30
2) Parameter control	.25
3) Heat transfer efficiency	.20
4) Manufacturability	.15
5) Cost	.10
	1.0

Reliability was given the highest weighting because of the importance of the resistojet performing its function as needed. If the jet fails to produce the required impulse the result of altitude loss could be detrimental to station performance. The second highest weighting was given to parameter control because if pressure, temperature, and flow rate cannot be maintained at the values required to provide the necessary thrust and prevent condensation in the chamber, then the resistojet does not adequately serve its purpose. Heat transfer efficiency received the next highest weighting and concerns both the efficiency of the heater in converting the electrical power it receives into thermal energy and how uniformly it heats the passing flow of gases. The second to the lowest weighting was given to manufacturability of the heating component. The more difficult the heating element is to make, the more costly and difficult it is to replace. Also, a simple design may already be on the market eliminating the need to design and build a heater from scratch. Cost was given the lowest weighting because it is not a driving force in the design of the resistojet relative to the other criteria, but nonetheless, it is a constraint and NASA's budget for space station is limited, therefore it was included in the criteria. Safety was originally considered as part of the weighting criteria, but it was determined that all of the heater configurations were rated equally for safety, thus it was eliminated.

In the decision matrix shown in Appendix D, the concept variants are rated 1 to 6 on how well they satisfy each of the weighting criterion. Then the rating is multiplied by the weighting factor for that particular criterion and the resulting products are added together in the SUM column. The concept variant with the highest sum best satisfies all of the evaluation criteria. Some of the variants were given equal ratings in several areas where no differentiation could between how well each variant satisfied the evaluation criteria.

For control, ratings were determined on the basis of how uniformly the gases could be heated. The more evenly the gases are heated, the more accurate the temperature measurements will be, and the better the temperature can be controlled. The heated spheres cause the most uniform heating to occur while the cylindrical rods have the smallest surface area and least even heating.

Cost ratings were determined on the basis of availability of the heating elements. Variants 1,3, and 6 are fairly simple designs already in existence and widely used, whereas heated spheres are not as common and would have to be manufactured specifically for the resistojet. Ratings for manufacturability were determined on a similar basis and also considered the connection to the chamber casing, the connection of heater parts to each other, surface finish, and ease of formation.

Heat transfer efficiency is a function of contact surface area and the time the gases spend in the heat interaction area. The finned coils variant was given the lowest rating since the flow passes right by the coils and the surface area contacted by the gases is small, whereas the gases get heated the most by the heated shell and the spheres.

Reliability was based on the simplicity of the variant. The heaters with the fewest components and the best working record received the highest ratings.

The heated shell with internal and external flow was selected as the final concept based on the fact that it best satisfies the evaluation criteria. The external heater variant and the internal coil variant follow close behind as expected given that the heated shell is a combination of these two concepts.

Feasibility Analysis

Upon performing preliminary calculations on the resistojet using the selected concept, the flow was restrained to the operational conditions addressed below. Based on these conditions, the chamber could not exceed a 9.7 mm inside diameter. This geometry limited the internal/external heater element configuration which could be used. In fact, manufacturing the selected heater configuration was seen as a highly expensive process, if it could be performed at all. Instead of struggling with the issue of trying to make the internal/external flow configuration work, it proved to be more feasible to work with an internal flow heating configuration to meet the restraints of the flow. The internal flow heating element could easily be applied by using a cylindrical sleeve with a resistive coil wrapped around it. The analysis below justifies the selection of the internal flow heater element configuration.

ANALYSIS OF RESISTOJET OPERATION

The resistojet analysis began by reviewing specifications, and then imposing several operating conditions in order to develop operational parameter requirements. This method of analysis seemed to be the most logical approach since it produced values which were specifically tailored for this resistojet operation. Another alternative analysis method considered was the selection of parameters based on available resistojet technology with similar operating conditions. However, the available resistojet technology uses single component fuel mixtures and larger thrust requirements. Due to the unique nature of the multi-component waste gas mixture and the desired low thrust range involved in this design, the alternative approach was not used.

Furthermore, since the operation of the resistojet deals with waste gas compositions that vary from one burn cycle to the next, the resistojet analysis was performed using100% compositions of each gas. That is, each of the five waste gases were independently analyzed as it flowed through the resistojet. By doing this, an operational window was created based on the high and low values produced by each waste gas. Assuming that there are no chemical reactions occurring within the resistojet, all mixture compositions should produce operational values which fall within this operational window.

Review of Specifications

The specifications of immediate impact to the parameter development were the desired thrust range, the pressure within the resistojet, and the cold flow mode of operation. The thrust range specified for this resistojet was from a minimum of 0.22 N (50 mlbs.) to a maximum of 1.6 N (350 mlbs). In order to guarantee the minimum and maximum thrust, the analysis was performed from minimum thrust, minus 5%, to maximum thust, plus 5%.

The desired pressure within the resistojet chamber was 552 KPa (80 psia). However, during the thermodynamic analysis of the waste gas flow, it was discovered that the thrust produced by the resistojet is proportional to the pressure within the resistojet chamber and the nozzle throat area. Therefore, in order to vary the resistojet thrust, either the throat area or the chamber pressure would have to be varied. Since varying the throat area seemed to produce a complex mechanical issue, it was decided that the chamber pressure would be varied. The 552 KPa (80 psia) requirement was used at the maximum thrust, not including the +5% thrust compensation. By choosing 552 KPa as the highest operational pressure, the gases are maintained as ideal gases in any mode of operation. The minimum thrust, not including the -5% compensation, required a pressure of 68.95 KPa (10 psia).

An analysis of each of the five waste gases at several temperature and pressure states throughout the system showed that H_2O and CO_2 are not always in their ideal gas state. At the tank conditions, these two components are in nonideal states. However, when H_2O and CO_2 are transported to the resistojet and the chamber pressure is the maximum pressure required for maximum thrust, then they become ideal. These waste gases stay ideal regardless of the temperature setting. For this reason, the condition of maximum pressure and no temperature control is denoted as the "cold flow" condition.

Another specification that was addressed but was not directly incorporated in the embodiment design of the resistojet was the direct venting of waste gases. The purpose of the resistojet is to provide thrust to the spacecraft while at the same time venting waste gases that are produced by spacecraft operation. Based on this requirement alone, some degree of the venting specification was met. During the analysis of the operational parameters, an effort was made to vent as much waste gas as possible for a specified resistojet impulse. The minimum diameter allows for venting of more waste gases if the waste gas composition is not 100% argon.

Operational Conditions

Based on these specifications, several operational conditions were imposed in order to provide resistojet functionality. The first operational condition began with the assumption that all gases were in their ideal state and that any nonideal substances were a neglible part of the composition. This assumption is necessary in order to use the analytical formulas developed for gas flow. In trying to insure that all the waste gases were ideal, the resistojet pressure was maintained at 552 KPa (80 psia) or less.

The second operational condition is that the flow remains laminar throughout the resistojet system. The condition of laminar flow is necessary to properly analyze and control the heat transfer from the heating element to the gases within the resistojet. The laminar flow condition was enforced by targeting a Reynolds' Number value of 1900 and using the Reynolds' equation in conjuction with a mass rate equation to determine the chamber diameter which would satisfy this condition. The equations used in this analysis can befound in Appendix F and the calculations for the resistojet operation can be found in Appendix G.

Two other operational conditions are based on having negligible friction as the waste gas interacts with the heating chamber surface. Negligible friction is necessary especially in treating the flow in the chamber as Rayleigh flow and the flow in the nozzle as isentropic flow. These two conditions are necessary in order to simplify the flow analysis within the resistojet. Furthermore, the operational conditions based on negligible friction increase the operational stability of the resistojet.

Determination of Remaining Parameters

Based on the analysis performed for expansion of the waste gases, the resistojet dimensions for the nozzle throat diameter and the chamber diameter were determined. Several dimension restrictions were listed in the specifications. The only dimensions remaining are the diameter of the tube connecting the tank to the entrance of the resistojet and the exit area of the nozzle. The diameter of the tube from the tank depends directly upon what NASA chooses, this dimension was unknown at the time of analysis. The assumption was made that the resistojet inlet diameter does not significantly affect the flow of the waste gases. For this reason, the inlet tube was chosen to be half of the chamber diamete.

In searching through the available resources on resistojet technology, several sources were found which were helpful in determining the exit area of the nozzle. Pugmire's article contains a resistojet analysis which is very similar to the analysis using waste gas expansion. For this reason, it was decided that the nozzle dimensions provided by the source would be just as valid for the waste gas resistojet. Otherwise, the determination of the nozzle exit area would have been performed using an iterative method and a guess of the final dimension from several candidates.

OPERATIONAL CONTROL

System description.

The operation of the resistojet will be controlled by a MRAC (Modal Reference Adaptive Control) system. A mathematical model of the resistojet system will be incorporated into an algorithm that will then determine what changes to make in the resistojet system. The algorithm tells the controller the amount of change that has occurred in the flow regulator and PCU (Power Control Unit) for a given signal level. The signal levels are calibrated by test procedures performed preflight. The algorithm also decides which parameters to change. As a default setting for the algorithm, the control of the flow regulator will be the first to be executed. This is done because the resistojet will respond quickly to flow regulation as opposed to temperature regulation. However, if the resistojet cannot produce the amount of impulse needed for a given temperature and the flow regulator is at a maximum output, the controller will then increase the temperature until the required impulse is achieved.

Unlike other types of controllers that require an exact model of a system, the mathematical model to be used by the MRAC system will estimate values for temperature, pressure, flow rate, and thrust. These values are used as references for the actual values. The MRAC system is especially suited for controlling the resistojet system because it does not have to have insight into every parameter in the system. Since the composition of the waste gases varies over time, it would be difficult to derive an exact model for the system. A MRAC system uses estimated values to determine appropriate settings for proper control of the system. The MRAC system essentially adapts to the changing conditions of the resistojet system (namely the varying waste gas composition). The adaptive nature of the MRAC system allows it to continuously search for the optimum settings within an allowed tolerance range by using an orderly trial-and-error process and it allows for performance superior to that of a fixed system [Chalam, 8].

The basic equations that define the system operation are given in equation's 1a and 1b. These are called state equations and considered the mathematical model for the resistojet system.

$$\dot{\hat{x}} = A\hat{x} + Bu \tag{1a}$$
$$\hat{y} = C\hat{x} \tag{1b}$$

Equation 1a is the mathematical model of the resistojet system and contains all the necessary equations to determine the state of the system, (i.e. waste gas mass rate, pressure, etc.). As mentioned before, these states are estimated because of the variation in composition of the waste gases. The input to the mathematical model is the pressure and impulse. The model then estimates the pressure, flow rate, and temperature needed to attain the required impulse. It is assumed that the initial thrust, or cold thrust, will be significant enough to be included in the system model.

Equation 1b is a matrix that contains the output conditions, which in the case of the resistojet system is the impulse.

The actual states are determined by transducers placed on the resistojet system. A pressure transducer will be used to measure the pressure of the gas exiting the tank and entering the resistojet. For measuring the thrust, a load cell will be situated immediately behind the resistojet. The transducer measurements will be processed and arranged into the same state equations which are written as follows,

$$\dot{x} = Ax + Bu \tag{2a}$$
$$y = Cx \tag{2b}$$

Subtracting equations 2a from 1a and 2b from 1b we obtain,

$$\dot{x} - \dot{\hat{x}} = A(x - \hat{x}) \tag{3a}$$
$$y - \hat{y} = C(x - \hat{x}) \tag{3b}$$

The difference between the actual and estimated states is then used to adjust the system settings. If the resistojet system is stable, in that it has reached an expected thrust for example, then the difference approaches zero. However, if the controller detects a difference between the actual and estimated values that is beyond tolerance levels, then it will proceed to change the system parameters, based on the algorithm, to make the difference approach zero. The control of the system will be done by pressure regulation and temperature control.

The tolerance to be allowed by the controller is assumed to be ±2% of the actual thrust. This means that the controller will maintain the actual thrust to within 2% of the desired thrust for correct impulse.

The controller will have two modes of operation to fulfill the requirements of the space station. The first mode of operation will be to provide a desired impulse. The impulse is attained by having the controller record the thrust, via load cell, in real time and multiplying it by the time over which it was recorded. This is done continuously and added cumulatively until the required impulse is reached. Figure 2 shows an example of how the impulse is calculated.

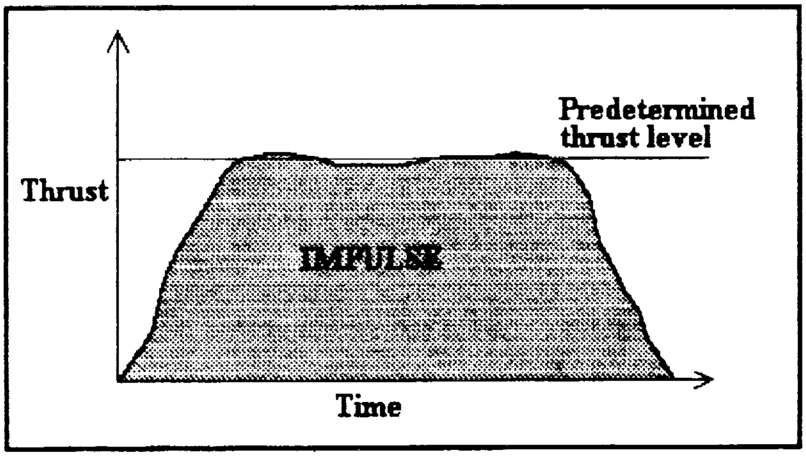


Figure 2. Impulse diagram with the actual thrust recorded over time. The impulse is calculated by multiplying the thrust by the time over which it was recorded.

If a large impulse is required, then the controller will operate the resistojet at a predetermined level of thrust. This thrust level can range from one fourth to one half of the rated maximum thrust. There are two reasons for these settings, one reason is to conserve power and the other is to minimize material degradation.

The second mode of operation is considered a "cold" mode. In this mode, the controller will allow the resistojet to vent the waste gases at a minimum thrust. This is attained by turning the PCU off and opening the pressure regulator to maximum.

Parameter Measurement

Pressure. A pressure transducer is placed in the flow path of the waste gases to measure pressure and is situated near the entrance of the resistojet. The controller continuously monitors the pressure for variations and adjusts the pressure regulator to maintain the proper pressure for a given thrust.

Temperature. High temperature Inconel, ceramic fiber insulated, type C thermocouples are used to measure the temperature along side of the resistojet. This type of thermocouple can withstand harsh environments, such as space, without sacrificing accuracy. The temperature measurements are used for determining the actual temperature of the resistojet. Since the temperature on the outside of the resistojet is not representative of the true temperature, approximate temperature values are calculated to determine the best estimates.

Thrust. The measurement of the thrust is achieved by the use of a load cell situated immediately behind the resistojet with a ceramic insulator placed in between for heat protection. The load cell emits an electrical signal when a force is exerted on it. The controller is calibrated with the signal across all load ranges during testing. It will have a 0 to 5 lbs (0 to 22.25 N) load range with .005% full range repeatability.

Parameter Control

Thrust. The thrust of the resistojet is controlled by regulating the pressure of the waste gases as they enter the resistojet. As a consequence, the amount of impulse will vary depending on the amount of thrust, (i.e. a higher thrust would mean a shorter impulse as opposed to a lower thrust for a longer impulse). However, since there is a limited amount of waste gases in the storage tanks before they are refilled, a time limit will be set to get the most impulse from the available waste gases. The amount of thrust would thus depend on the impulse limit imposed on the controller.

PCU. The temperature of the heating element would be regulated by the controller via the PCU. The controller adjusts the temperature in accordance with impulse within a range of temperatures up to 1400°C (2552°F). However, three settings will be used for the resistojet system. The first is a "cold" setting in which the heating element is not heated. This will allow for "cold" thrust and venting of gases with minimal impulse. The second setting will allow the controller to maintain the temperature between 300°C and 500°C (572°F to 932°F). This temperature range will keep the gases, primarily H_2O and CO_2 ,from condensing in the resistojet chamber and will prevent hydrocarbon cracking when hydrocarbons are present. The last setting allows a maximum temperature that would allow a maximum impulse.

Cable protection. All cables that connect the resistojet system to the controller will be protected by Nextel® ceramic fiber. This fiber is able to withstand extreme temperatures and the harsh environment of space and thus protecting the cables. A redundant cable network is connected to the resistojet system in case of cable failure.

Emergency shutoff system. The controller serves three functions for safety of the crewmembers as well as the space station. The first function of the controller is to continuously monitor the status of the resistojet system via temperature and pressure. The second function is to alert the crew and the third is to shut the resistojet system off in the event of an emergency. In the event of a manifold rupture, for example, the controller would detect a sudden drop in pressure and signal an alert. At the same time, the controller would automatically shut off the pressure regulator to prevent further waste gas leakage.

Calibration. The calibration of the controller will be conducted in an Earth-based test area. The pressure transducer will be subjected to various, known pressures. The MRAC controller will then be calibrated at each pressure for the entire range of expected pressures. The same procedure will also apply to the thermocouples. The thermocouples will be subjected to the various temperatures to be expected. The test will be conducted in a vacuum environment with the ambient temperature the same as that in space to obtain accurate output signals from the thermocouples. The load cell will be calibrated using a set of known weights. A known set of weights will be applied to the load cell and the signal output from the load cell will then be calibrated into the controller.

MATERIALS SELECTION

Selection Procedure

The selection process of materials is the next step to linking the conceptual model to design production and optimization. This section of the report will discuss the selection procedure used. A systematic procedure of combining environmental conditions and functional requirements with selection criteria and material properties was used to effectively choose the appropriate materials, . This selection process is limited to the scope of the defined conceptual system, specifically the resistojet itself. Through the selection process, the proper materials are matched with the conceptual model.

As detailed in the previous sections, the design conditions of the system require specific materials. One of the primary considerations is the functional requirements. The basic functions required by this system are ventilation and altitude control. These operations are constrained by the demands for extended operational life and the intrinsic degrading properties of the various propellants. Additionally, it is a necessity for the system to control any impinging contamination of the spacecraft environment. With the adoption of these functions, the next step in optimizing the selection of materials is to detail the environment within the system boundary. The majority of this step has been done in the previous sections of this report. Externally, the general conditions of operation are the near zero gravity and pressure of earth's orbit. The drag forces and their variation are one of the sources of the motivation of the design. Internally, the resistojet will be subjected to conditions of relatively high temperatures and pressures, along with an interface between the flow of waste gases propellants. While the variation of operational parameters of temperature and pressure have been defined in the previous section, the conditions of the propellants are notably variable. To provide a base for comparison of atmospheres, a table of the various types of furnace atmospheres are listed in the Appendix H. With these design conditions the selection process can be continued.

Development of Selection Criteria

To procede with the embodiment of the resistojet, the design parameters were used to develop the criteria for the selection of materials. By grouping the specifications and required material properties into three categories, an exhaustive list of selection factors was created (See Appendix I). These points were then condensed into important selection factors. The selection of the different materials were judged based on these 9 points. They are as follows:

1. Creep. The material must withstand the thermal cycling of the temperature variation over its projected lifetime.
2. Environmental Resistance. The material must maintain an erosion corrosion resistance of no more than a 10% loss during the projected life. Additionally, the reaction of the multipropellant gas to the system must not produce effects which sufficiently shorten the projected life.
3. Electrical Properties. The heating element must sufficiently convert electrical power resistively into thermal energy.
4. Conduction. Heat transfer from the heating element to the fluid flow must be effective. The system also must guard against thermal contamination of the space craft.
5. Temperature Capacity. The materials must maintain its structural integrity at the maximum projected temperature of operation.
6. Quantity. The projected production will be limited to 8 units and 2 spares.
7. Manufacturability. The materials must be able to maintain a pressure tight configuration for the projected flow of fluid. The materials choosen must be producible in terms of the resistojet design. Previously manufactured materials are considered premium.
8. Service Life. The materials must have at least an operation life of at least 10,000 hours.
9. Cost. The materials selected will be evaluated to consider the relative costs of the materials and their manufacture.

Design and Selection.

To begin the design and selection of materials, a list of general parts was developed. By incorporating the environment and the selection criteria for each specific part, the design of the structural members of the resistojet was possible (See Appendix I.). This section will discuss the specific design and development of the individual parts.

Alloy Selection. The materials selected for the heating element will be the most crucial to the success of the design. The heating element's operation is significant to the continued operation of the resistojet. First, a material must be capable of converting electrical power resistively into thermal energy. Additionally, the heating element must withstand high temperature corrosive environments and thermal cycling. High temperature operation requires that the material selected maintains its strength as temperature increases.

These types of electrical resistance alloys are known as heating alloys, and they range from various metallic alloys of nickel or iron to pure metals and nonmetallics. The materials that are capable of heating to the temperatures required by the design are somewhat limited (See Table 1.). Several of the materials are limited by the requirement of operation with certain environments. For the design of the conceptual heating element, it was assumed that the operating environment varies by composition. The only materials that are capable of operating at the required temperature in air are platinum, silicon carbide (SiC), and molybdenum disilicide ($MoSi_2$). All have excellent oxidation resistance in air at elevated temperatures. Platinum, however, is not recommended for heating various atmospheres, specifically H_2. $MoSi_2$ is unique in this group in that it maybe used with excellent corrosion resistance at elevated temperatures in predominately all atmospheres (See Table 2.). The resistance to corrosion is the result of a film of silica glass that forms on the surface of $MoSi_2$ at 980° C [ASM Metals Handbook, p.640-648].

In comparing the high temperature strengths of platinum and $MoSi_2$, the design team sought to continue to evaluate the selection of a heating alloy. Research conducted by NASA and various contractors have found that two types of grain-stabilized platinum (yttria [Y2o3] and zirconia [ZrO2]) increase their creep resistance and high temperature strength [Whalen, p.540]. The research also states that ammonia causes detrimental effects to the structural integrity of platinum. $MoSi_2$ shows a stark contrast to platinum's strength. Pure $MoSi_2$ at room temperature is too brittle for reasonable use. However, by adding a mixture of 10% ceramics, the brittle behavior is controlled for industrial application. In fact, the nonmetallic has properties described as "self-healing" due to the plastic formation the thin silica film. This self-healing characteristic has been credited for the successful cycling of $MoSi_2$ from room temperature to 1650° for 20,000 cycles. Still the tensile strength of $MoSi_2$ plus 10% ceramic additives is half of platinum and this factor is worse for SiC which is too brittle to be considered in this application [ASM Metals Handbook, p.640-648]. (The rest of the report will refer to $MoSi_2$ (+ 10% ceramic additives) as $MoSi_2$).

Table 1.

Heating Alloys Applicable to the Resistojet Temperature Specifications

Basic Composition, %	Approximate Melting Point		Maximum Furnace Operating Temperature	
	C°	F°	C°	F°
Pure Metals				
Molybdenum *	2605	4730	1650	3000
Platinum	1770	3216	1500	2750
Tantalum *	2975	5390	2480	4500
Tungsten *	3375	6116	1650	3000
Nonmetallic Materials				
Silicon Carbide	2410	4370	1600	2900
Molybdenum Disilicide	2040	3775	1700 to 1900	3100 to 3270
MoSi2 + 10% ceramic add.	1800	3270	1700	3100
Graphite *	3650 to 3695	6610 to 6690	2205	4000

* Temperatures valid for operation in inert or vacuum environments only.

Source: ASM Metals Handbook, 1983.

The design team chose to use $MoSi_2$ in the embodiment of the heater configuration The judgement was based on the nonmetal's ability to maintain its structural and functional capacity at high temperatures, specifically in the atmospheric conditions of the possible waste gases. $MoSi_2$ is the only material that is recommended for use for all the projected waste gases aboard the station at the temperatures specified for the design. The team considered the additional cost of the processing and fabrication needed by $MoSi_2$ to be significantly less than the exorbitantly high cost of platinum (\$5,038/in^3 or \$6,500/lb compared to approximately \$25/in^3 or \$30/lb) [Budinski, p.597]. $MoSi_2$.additionally maybe applied to structures as a plasma spray.

Table 2

Maximum service temperatures for $MoSi_2$ heating elements

Atmosphere	Temperature C°	F°
Air	1700	3100
Nitrogen	1590	2900
Argon, helium	1450	2730
Dry hydrogen	1350	2460
Moist hydrogen	1460	2660
Carbon dioxide	1590	2900
Carbon monoxide	1450	2730
Sulfur dioxide	1590	2900
Partly burnt ammonia	1400	2550
Methane	1350	2460

Source: ASM Metals Handbook, 1983.

Heating Element Design. The design of the heating element consists of a double helix coil as shown in Figure 3. The coil carries the current loop and is resistively heated radially out towards the surface of the material. This element is functionally available and has been used successfully in previous designs. The coil apparatus consists of a platinum-rhenium (Pt-10Rt) heating element insulated with a magnesia (MgO) ceramic. This wire is then enclosed in a platinium sheath. The design team seriously considered using a different material for the coil. However, in the overall consideration of the design, the cost and manufacturing issues of a heating element made of $MoSi_2$ was judged to be impractical and non-cost effective. The team did opt for a modification to the coil apparatus. In previous applications, designers had chose to change the Pt-10Rt sheath to a grain stabilized platinuim alloy as mentioned before [Morren, p.12]. The design team suggested the sheath consists of $MoSi_2$ deposited by Chemical Vapor Deposistion (CVD). An analysis of the dimensions and a schematic of the heating apparatus is contained in Appendix J.

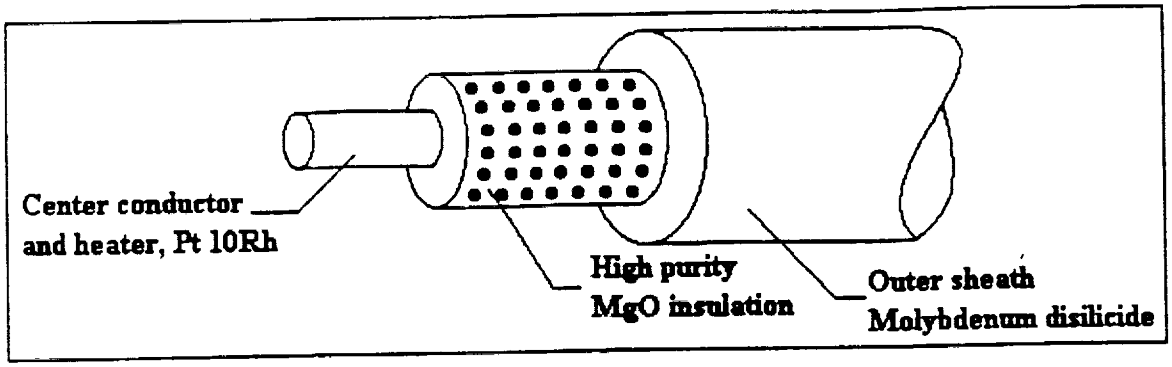


Figure 3. Heater coil. The coil design consists of a platinum wire with MgO insulation and a $MoSi_2$ sheath. This design is one that was modified by incorporating the $MoSi_2$ sheath for corrosion resistance.

Heat Exchanger Design. The design team choose to coupled the heating coil with an heat exchanger for the development of the thermal transfer process. The justification for this application is to protect the coil material from short circuiting and insure long life. Additionally, the efficiency of the heat transfer is not effected in a large amount. For the construction of this part, a $MoSi_2$ machined tube to perform as the heat exchanger. The selection of $MoSi_2$ results in a estimated cost savings of 98% for the production of the heat exchanger [Budinski, p.597]. The part will also be able to effectively resist the corrosive effects of the majority of available waste gases, including NH_3 which severely attacks platinium components. The downside to this selection is as $MoSi_2$ approaches its melting point (1800° C) there is evidence of plastic flow. Based on the maximum level of temperature that will occur in this system, the design team considered this factor to be reserved for further development in their recommendations.

Nozzle. The configuration of the nozzle is contained in Figure 4. The nozzle will be made of $MoSi_2$ with dimensions based on the theorhetical considerations presented with the system operation. This calculations are based on ideal flow which would produce an expansion nozzle of a half angle of 25°. The placement of $MoSi_2$ in the nozzle is critical to corrosion resistence. The inlet diameter will see the greatest amount of mass flow through the system operation. Additional concerns include the design of the external plume shield against the exiting mass flow and the protection of the space craft from contamination. These issues will be discussed in the design of the casing.

Thermal and Radiation Shielding. Radiation shielding defines the ability of the jet to maintain its efficiency during high temperature operation. The level of temperature into the subsquent shielding is on the order of 75% and 30% in previous designs of the resistojet. The design team considers the thermal protection of the load cell to be critical to its operation. A layer of ceramic insulation (an inch compacted MgO) was included surrounding the heater coil. This should improve the efficiency of the heating apparatus as well as save the high cost of platinium. Between the casing will be additional nickel coated alumina shielding from INCO® Specialty Powder Products. The high purity nickel coating will insure the structural integrity resistence. Alumina will also be incorporated into the mounting structure of the jet to assure thermal shielding.

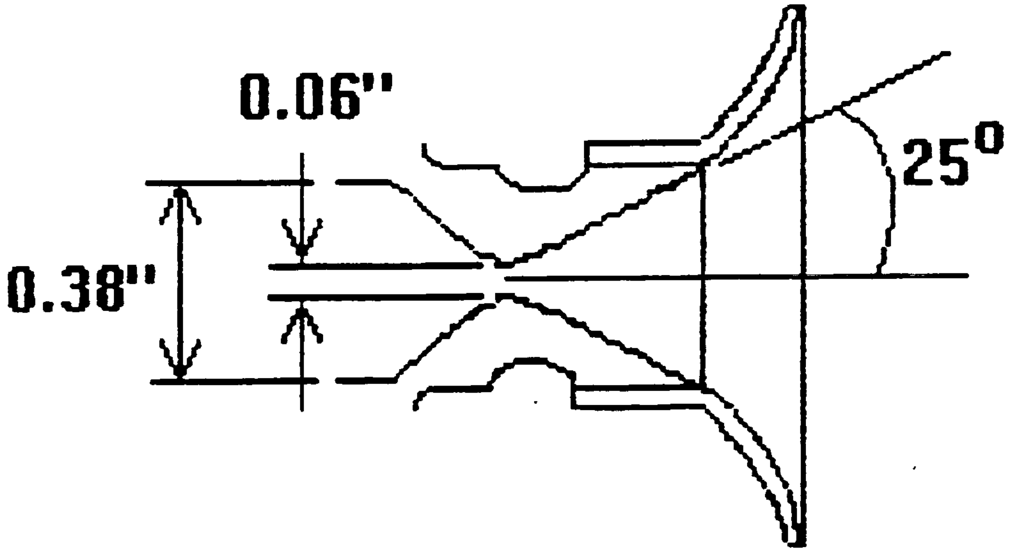


Figure 4. Nozzle configuration. Based on the calculations of the operating conditions, the dimensions of the nozzle have been produced. The material selected for the nozzle is $MoSi_2$.

<u>Casing and Plume Shield.</u> The casing of the resistojet uses Inconel® 600 alloy to provide the structural protection for the exposure to space. Inconel 600 has excellent properties for applications in space. The design team also choose to incorporate this alloy for the plume shield because of its superior corrision resistant properties. The plume configuration is posed at 45% around the edge of the jet. For the expansion of the expelled gases, this will provide the maximum amount of protection to the space craft [Morren, p.18]. A schematic of the materials selected for the resistojet is presented in Figure 5.

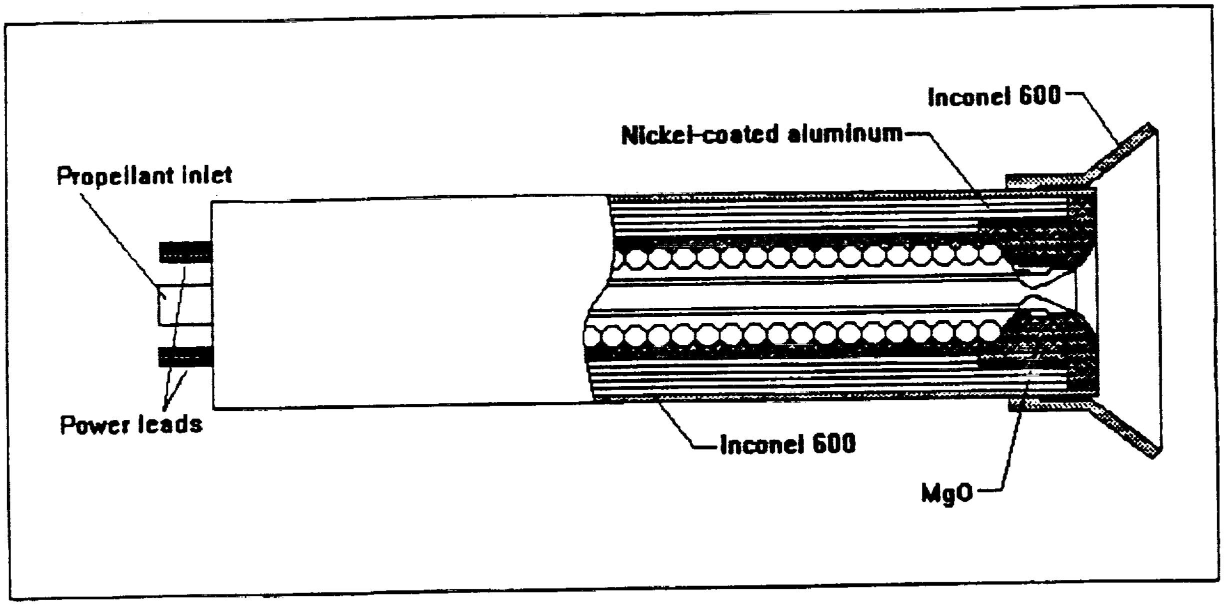


Figure 5. Resistojet materials. The schematic shows the materials and their configuration as preposed by the design team. $MoSi_2$ has been choosen to replace platinum in numerous sections of previous designs. The design team estimates a cost savings of 98% over the use of platinium and asignifigant increase in the types of waste gases that may be vented through the resistojet.

DESIGN OF TEST PROCEDURES

The testing of the entire resistojet system consists of a test apparatus set up in a vacuum environment. The setup consists of a mock-up of the structure station onto which the resistojet system will be attached.

A load cell is used as the measuring device for the thrust and will be situated immediately behind the resistojet. The load cell has a Nextel® ceramic insulator to minimize or eliminate the effects of temperature. The resistojet will be tested for the complete range of operating temperatures and pressures specified by NASA. However, a safety margin for the resistojet will be used. Although the maximum temperature that the heating coils will encounter is 1400°C, tests conducted by the American Society of Metals on molybdenum disilicide concluded that the material can withstand 20,000 temperature cycles up to 1650°C without serious degradation. In the unlikely event that the resistojet experiences such a high temperature, there will be no permanent damage to the resistojet itself. The pressure range that the resistojet will be tested under will be from 0 to 1000 psia. Since the design and operation of the resistojet system does not call for pressures as high as 1000 psia, the resistojet should be able to sustain the pressure for a short amount of time before permanent damage occurs.

Other necessary testing procedures consist of quantifying the materials system to different atmospheres. This area of design is the most aggressive of the project. The use of $MoSi_2$, particularly in the design of the heat exchanger, also needs to be tested. The use of $MoSi_2$ in the heating coil is not as crucial to this project. There already exists a wide base of data from previous experimentation, and the use of the $MoSi_2$ sheath is not critical to the heating coil performance. The design team proposes that the heat exchanger be tested by developing a prototype and operating it at the specified conditions. To perform this test, a single resistojet should be mounted in an encapsulated ceramic mount. Thermocouples should be strategically attached to measure the actual temperatures produced by the system, and the resistojet should be tested with the waste gases aboard the space station. Post-firing analysis of corrosion and the microstructure will allow the prediction of performance and operating life. These tests are important to insuring the production and cost effectiveness of the resistojets.

CONCLUSION

A combination a ventalation and expansion of waste gases was designed for part of the required altitude control for future spaccraft. This report focused on resolving the issues of resistojet which include: system performance, flow and heater control, materials selection and design test procedures. The resistojet design was formed from a conceptual model of a shell wrapped by a resistive coil with gases flowing internally through the tube. Major parameters were calculated by analyzing each waste gas and show that the specified waste gas will behave ideally at this pressure at any temperature, but water and carbon dioxide tend not to behave ideally over different pressures. The design team designated 552 kPa and no temperature input as the "cold flow" condition and found that any ventilation under all conditions would produce thrust.. The design of the ventilation function was limited to recommendations. A proven "trial-and-error" controller was selected. The Model Reference Adaptive Control system was judged to fit the design since it will easily adapt to changes within the system. While plantinium was selected for the heating element of the coil, other elements in the system were replaced with $MoSi_2$ + 10% ceramics for an estimated cost savings of 98% in materials. The materials selected for the resistojet optimize environmental resistance and cost. Additionally, a variety of testing procedures were selected.

Recommendations

Several recommendations can be made to further develop the full potential of resistojet technology. One possible recommendation for future research is the possibility of using other mixtures of waste gases such as ammonia and hydrogen. This research may encompass further analysis into material selection.

Since a large part of the numerical analysis was greatly simplified by using ideal gas assumptions for the waste gases, further analysis can include calculations of temperature, pressure, mass flow rate, etc. at non-ideal conditions.

The resistojet in the embodiment design is limited to a thrust range no greater than 0.350 lbs. Further testing can be done to increase the thrust range to a maximum level while still meeting operational life requirments. Modifications can be made to the resistojet structure to help it withstand the higher pressures so that it can be implemented to provide greater impulse. The modifications can include stronger manifold attachments, resistojet chamber stiffening, material selections, etc.

A more accurate way of acquiring information about the temperature and pressure of the waste gases within the resistojet during firing can be attained by further research. Thermocouples and pressure transducers capable of withstanding the harsh environment of the resistojet can be implemented internally within the resistojet without adversely effecting the flow characteristics.

A key recommendation for further research is the venting of gases without producing thrust. Two alternatives can be tested, one is the venting of waste gases at a low pressure and temperature. The second alternative is installing two opposing bleed valves on the flow path to the resistojet. Opposing the bleed valves can eliminate net thrust and prevent the venting from imposing a moment on the space station.

Appendix A
Specification Sheet

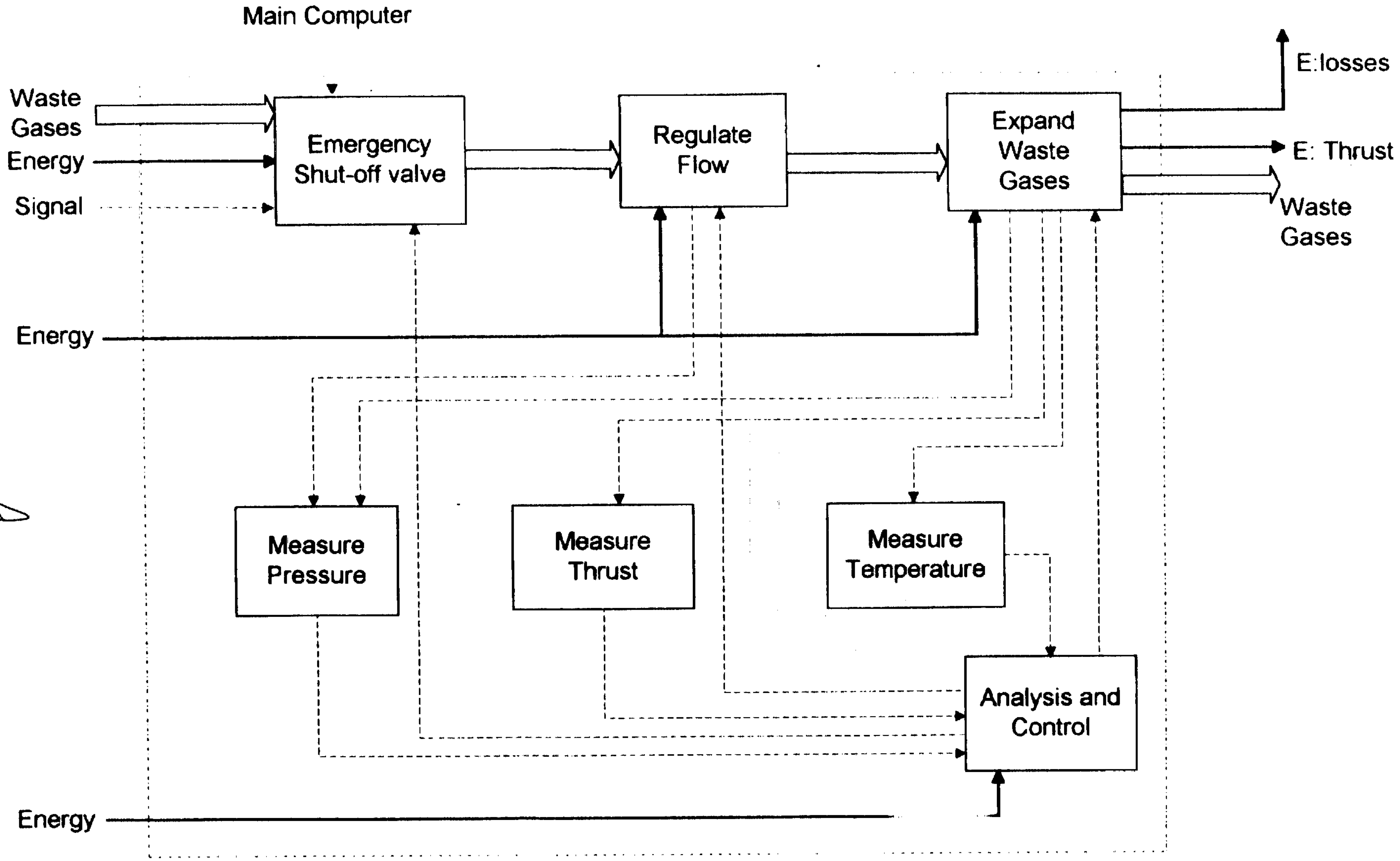
NASA *Johnson Space Center*	*Specification* for Resistojet	*page 1*

Chg	*D W C*	*Requirements*	*Rsp*	*Verify*
		1. Geometry		
	C	Jets not to exceed: 2.4" diameter casing		measure
	C	3.8" diameter nozzle exit		measure
	C	9.4" length of entire assembly		measure
		2. Forces		
	C	Thrust: 50 - 350 mlbs		measure
	C	Liftoff acceleration: 3.3 g		pre-launch testing
		Impulse: goal is $2\text{x}10^6$ lb_f/s over lifetime		measure
		3. Energy		
	C	Power : 500 W max to heating component		measure
	W	125 W average		measure
	C	Pressurized waste gases: 6 cu. ft.		measure
	D	Multipropellant capability		
		4. Material		
	D	Manifolds, casing, and nozzle: non-corrosive, working temp. range -50 - 1500 °F, compatible with all waste gases		pre-launch testing
	D	Failure criteria: 10% erosion over lifetime		performance check
		6. Signals		
	D	Control pressure regulation		measure pressure
	D	Temperature sensing		measure temp.
	D	Output of watt usage		measure
	D	Heater control and feedback		pre-launch testing
	W	Flow rate monitoring		measure flow rate

NASA Johnson Space Center	Specification for Resistojet	page 2

Chg	D W C	Requirements	Rsp	Verify
		7. <u>Safety</u>		
	D	Placed clear of EVA workstations, sensitive areas		check station
	D	Clearance should be 6" radially around jet		design
	D	Emergency shut-off capability built into system		measure
		8. <u>Ergonomics</u>		pre-launch test
	D	Repairable on orbit		
	D	Maximum of 2 crewmembers to repair		pre-launch test
	W	Prefer repair by single individual		pre-launch test
		9. <u>Production</u>		
	D	Integrated into structure pre-launch		
	C	8 units required, 2 additional spares		pre-launch test
		10. <u>Quality control</u>		count
	C	Lifetime: 18 yrs (10,000 thermal cycles over 18		
		yrs)		statistical analysis
	D	Testable in vacuum chamber or by other means		test in vacuum
		11. <u>Assembly</u>		
	D	Assembled and integrated into structure pre-		pre-launch fit test
		launch		pre-launch fit test
	D	Modular construction		test in vibration
		12. <u>Operation</u>		chamber
	D	Must meet NASA standards for vibration of station		
		13. <u>Cost</u>		detailed cost
	C	Not to exceed: $100,000 to $300,000 per jet		estimate
		14. <u>Maintenance</u>		
	D	Diagnotic capability built into system		test diagnostics
	W	Should have purging capability to flush contaminants out of manifolds		

Appendix B
Function Structure



A.

Appendix C
Solution Matrix

	Solutions to sub-functions					
Sub-functions	**1**	**2**	**3**	**4**	**5**	**6**
Regulate Flow	Simple Orifice	Mechanical Pressure Regulator	Electronic Pressure Regulator			
Expand Waste Gases	Internal/External flow thru shell	Flow across finned heater coils	Internal heater coil with external flow	Flow across heated spheres	Flow across cylindrical rods	Internal Flow and external heater
Measure pressure	Pressure transducer	Manometer	Pressure gauge			
Measure thrust	Load cell	Analytically				
Measure temperature	Thermocouple	Thermistor	Thermometer	RTD (1)		
Analysis and control	Software on main computer	P (proportional)	PD (proportional + differential)	PI (proportional + integral)	PID (proportional + differential + integral)	MRAC (2)

(1) Resistance Temperature Detector
(2) Model Reference Adaptive Control

Appendix D
Decision Matrix

DESIGN VARIANT	Parameter Control	Cost	Heat Transfer Efficiency	Reliability	Manufacturability	SUM
WEIGHT	.25	.10	.20	.30	.15	
Heated shell (int. and ext. flow)	4 1.0	4 .40	4 .80	3 .90	6 .90	4.0
Finned coils	2 .50	2 .20	1 .20	2 .60	2 .30	1.8
Internal coil	3 .75	4 .40	2 .40	4 1.2	5 .75	3.5
Heated spheres	5 1.25	1 .10	4 .80	1 .30	1 .15	2.6
Cylindrical rods	1 .25	3 .30	2 .40	2 .60	3 .45	2.0
External heater (internal flow)	3 .75	4 .40	3 .60	4 1.20	4 .60	3.55

Appendix E
Assumptions

1. The waste gases behave ideally within the resistojet during the expansion process. Any condensed substances have negligible masses when compared to the ideal gases.

2. Ratio of specific heat to specific volume is not pressure dependent, it is only a function of temperature.

3. The stagnation pressure and temperature at the entrance to the resistojet are the pressure and temperature found within the waste gas tank.

4. The section from the waste gas tank to the entrance of the resistojet is isothermal.

5. Chemical equilibrium is established within the chamber and does not shift within the nozzle.

6. The working fluid is homogeneous and invariant in composition throughout the chamber and the nozzle.

7. The waste gas flow is steady and constant with no flow vibrations or discontinuities within the resistojet.

8. The flow is laminar throughout the expansion process.

9. There is no pressure difference which exists between the inlet and outlet of the chamber during the expansion process.

10. Optimum expansion occurs within the resistojet system. This means the flow upstream of the nozzle throat is subsonic ($M < 1$), the flow at the throat is sonic ($M = 1$), and the flow downstream of the throat is supersonic ($M > 1$).

11. There are no shocks that occur within the resistojet system.

12. The friction produced between the gas and the chamber is small to negligible.

13. The flow within the nozzle section of the resistojet is isentropic.

14. The momentum of the exhaust gases leaving the nozzle is largely in the axial direction, with negligible momentum occuring perpendicular to the central resistojet axis.

15. Flow is ideally expanded at nozzle exit so that the exit pressure is equal to the ambient pressure ($p_e = p_a$).

16. The heat is uniformly distributed to the waste gas flow from the heating element.

17. The flow in the resistojet is choked flow, with a mach number of M= 1 existing at the nozzle throat.

Appendix F

Thermodynamic Analysis of Gas Flow

General Isentropic Flow

The following equations were used in analyzing the waste gas flow within the resistojet. These equations are used in conjunction with the assumptions listed in Appendix E.

For the isentropic flow found within the resistojet, including the nozzle, the following relations apply.

$$\frac{T_x}{T_y} = \left(\frac{p_x}{p_y}\right)^{\frac{k-1}{k}} = \left(\frac{V_y}{V_x}\right)^{k-1} \tag{1}$$

where x and y represent different points found within the isentropic flow, T represents the temperature, p represents the pressure, V represents the volume, and k represents the specific heat ratio.

The stagnation temperature or total temperature T_o is defined as

$$T_o = T + \frac{v^2}{(2c_p J)} \tag{2}$$

where T is the fluid temperature, v is the gas velocity, c_p is the specific heat constant, and J is a conversion constant.

Similarly, the stagnation temperature T_o is related to the stagnation pressure p_o using the relation

$$\frac{T_o}{T} = \left(\frac{p_o}{p}\right)^{\frac{(k-1)}{k}} = \left(\frac{V}{V_o}\right)^{k-1} \tag{3}$$

By using equation (2) in conjunction with the definition of the mach number (where a represents the speed of sound)

$$M = \frac{v}{a} = \frac{v}{\sqrt{kRT}} \tag{4}$$

a relation between the stagnation temperature and mach number is developed.

$$T_o = T\left(1 + \frac{1}{2}(k-1)M^2\right) \tag{5}$$

This equation can be use to determine mach number M in terms of temperature. The equation then becomes

$$M = \sqrt{\frac{2}{k-1}\left(\frac{T_o}{T} - 1\right)} \tag{6}$$

Isentropic Flow in a Nozzle

In analyzing the isentropic flow through a supersonic nozzle, the chamber temperature is considered to be equal to the stagnation temperature and also equal to the nozzle inlet temperature T_1. The nozzle outlet temperature is denoted as T_2. Using this notation, the nozzle exit velocity is

$$v_2 = \sqrt{\frac{2k}{k-1}RT[1 - \left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}}]} \tag{7}$$

where k remains constant throughout the flow process and the gas constant is R.

Since the flow in the resistojet is considered to be choked flow, the maximum flow in an isentropic expansion nozzle produces critical parameters. One of these critical parameters is the throat pressure required for maximum flow. The equation relating the throat pressure (critical pressure) to the inlet pressure is

$$\frac{p_t}{p_1} = \left[\frac{2}{(k+1)}\right]^{\frac{k}{k-1}} \tag{8}$$

Likewise, the equation for critical velocity v_t is

$$v_t = \sqrt{\frac{2k}{k+1} R T_1} = \sqrt{kRT_t} \tag{9}$$

and the flow mass rate equation through the critical section of the nozzle is

$$\dot{m} = \frac{A_t v_t}{V_t} = A_t p_1 \frac{k \sqrt{\left[\frac{2}{(k+1)}\right]^{\frac{(k+1)}{(k-1)}}}}{\sqrt{kRT_t}} \tag{10}$$

To determine a velocity of at a point x downstream of the throat, the following ratio is used

$$\frac{v_x}{v_t} = \sqrt{\frac{k+1}{k-1}\left[1 - \left(\frac{p_x}{p_1}\right)^{\frac{(k-1)}{k}}\right]} \tag{11}$$

The most critical equations used in the analysis deals with the thrust. Normally, thrust is a function of pressure and temperature

$$F = v_2 \dot{m} + (p_2 - p_3) A_2 \tag{12}$$

where temperature directly affects the mass rate $\dot{m}$ and the exit velocity v_2.

However, in the case of the resistojet, the ambient pressure p_3 is equal to zero because of the space environment. Further analysis of equation (12) leads to the following

$$F = A_t p_1 \sqrt{\frac{2k^2}{k-1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\left(\frac{p_2}{p_1}\right)^{\frac{K-1}{K}}} + (p_2 - p_3) A_2 \tag{13}$$

which reduces down to

$$F = A_t p_1 \sqrt{\frac{2k^2}{k-1}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{14}$$

because optimum expansion requires that the exit pressure p_2 be equivalent to the ambient pressure which is zero. Equation (14) shows that the resistojet thrust is directly dependent on the chamber pressure.

Appendix G
Performance Calculations

0.2 N

ThrtPrss(Pa)	ThrtTemp(K)	ThrtVel(m/s)	TMssRt(kg/s	Exit Velocit	Thrust(N)	DschrgTime(s)
36430.946	226.9129	306.990798	0.0003	752.4774	0.22318	49812.70193
36420.854	226.8307	301.91906	0.0003	739.3758	0.22305	51198.9615
37620.028	236.6632	241.134853	0.0004	667.1864	0.24177	0
33594.591	204.2279	266.100092	0.0004	532.4399	0.2	57989.77908
37253.41	233.6419	378.736811	0.0002	1006.0428	0.23511	726950.6663
ThrtPrss(Pa)	ThrtTemp(K)	ThrtVel(m/s)	TMssRt(kg/s	Exit Velocit	Thrust(N)	DschrgTime(s)
36611.348	480.8489	444.416342	0.0002	1107.4414	0.2255	72557.04982
36674.652	481.9367	436.660354	0.0002	1094.5834	0.22635	74693.03735
38695.849	517.1128	344.769546	0.0002	1102.6177	0.26893	0
33594.591	429.9915	386.115649	0.0003	772.5791	0.2	84144.13164
37625.269	498.3736	546.837283	0.0002	1513.9441	0.24187	1063347.021
ThrtPrss(Pa)	ThrtTemp(K)	ThrtVel(m/s)	TMssRt(kg/s	Exit Velocit	Thrust(N)	DschrgTime(s)
36868.542	654.6094	514.445113	0.0002	1313.8245	0.22907	84735.21776
36939.747	656.2652	505.410704	0.0002	1299.8623	0.23012	87245.0748
38988.818	704.5331	398.781406	0.00[illegible]	1338.6009	0.27928	0
33594.591	580.0365	448.451143	0.0002	897.3062	0.2	97728.57463
37921.863	679.2509	632.582415	0.0001	1815.1738	0.24808	1243028.797
ThrtPrss(Pa)	ThrtTemp(K)	ThrtVel(m/s)	TMssRt(kg/s	Exit Velocit	Thrust(N)	DschrgTime(s)
37529.918	1450.0232	750.209932	0.0001	2054.3499	0.24004	126441.9716
37558.931	1451.4947	737.434148	0.0001	2026.0568	0.24059	130070.5184
39418.49	1546.8892	583.047765	0.0001	2122.4488	0.29812	0
33594.591	1255.2390	659.706396	0.0002	1320.0070	0.2	143766.3091
38840.345	1517.0027	918.834749	0.0001	3007.7213	0.27382	1866051.513

1.6 N (~ 350 mlbs Thrust)

Gas	Strg Mss (kg)	Temp (K)	Pressure (Pa)	R (J/(kg*K))	Cp (J/(kg*K))	k	KtcVsc(m^2/s)
Nitrogen	14.77	272.22	551584.00	296.8000	1040.0000	1.3994	2.377E-05
Air	15.45	272.22	551584.00	287.0000	1004.1000	1.4002	
Carbon Dioxide		272.22	551584.00	188.9200	817.6000	1.3005	1.198E-05
Argon	21.78	272.22	551584.00	208.1300	520.7000	1.6659	2.127E-05
Water	169.89	272.22	551584.00	461.5200	1859.0000	1.3303	1.792E-06
Gas	Strg Mss (kg)	Temp (K)	Pressure (Pa)	R (J/(kg*K))	Cp (J/(kg*K))	k	KtcVsc(m^2/s)
Nitrogen	14.77	573.15	551584.00	296.8000	1069.9000	1.3839	
Air	15.45	573.15	551584.00	287.0000	1045.2000	1.3785	
Carbon Dioxide		573.15	551584.00	188.9200	1060.6000	1.2167	5.224E-05
Argon	21.78	573.15	551584.00	208.1300	520.7000	1.6659	7.891E-05
Water	169.89	573.15	551584.00	461.5200	1999.5000	1.3001	7.359E-05
Gas	Strg Mss (kg)	Temp (K)	Pressure (Pa)	R (J/(kg*K))	Cp (J/(kg*K))	k	KtcVsc(m^2/s)
Nitrogen	14.77	773.15	551584.00	296.8000	1116.3000	1.3622	
Air	15.45	773.15	551584.00	287.0000	1092.7000	1.3562	
Carbon Dioxide		773.15	551584.00	188.9200	1158.8000	1.1948	8.961E-05
Argon	21.78	773.15	551584.00	208.1300	520.7000	1.6659	
Water	169.89	773.15	551584.00	461.5200	2130.8000	1.2765	1.343E-04
Gas	Strg Mss (kg)	Temp (K)	Pressure (Pa)	R (J/(kg*K))	Cp (J/(kg*K))	k	KtcVsc(m^2/s)
Nitrogen	14.77	1673.15	551584.00	296.8000	1261.2000	1.3078	
Air	15.45	1673.15	551584.00	287.0000	1226.7000	1.3054	
Carbon Dioxide		1673.15	551584.00	188.9200	1346.2000	1.1632	
Argon	21.78	1673.15	551584.00	208.1300	520.7000	1.6659	
Water	169.89	1673.15	551584.00	461.5200	2703.4000	1.2059	5.601E-04

Reduced Temp	Reduced Press	ThrtDia(m)	ThrtPrss(Pa)	ThrtTemp(K)	ThrtVel(m/s)	TMssRt(kg/s)	NzStgTemp(K)	Inlet Dia. (m)
2.1571	0.1625	0.0015	291451.80	226.9129	306.99	0.0024	272.22	0.0098
2.0545	0.1463	0.0015	291371.05	226.8307	301.92	0.0024	272.22	#DIV/0!
0.8949	0.0748	0.0015	300964.59	236.6632	241.13	0.0029	272.22	0.0151
1.8028	0.1132	0.0015	268760.62	204.2279	266.10	0.0030	272.22	0.0097
0.4206	0.0250	0.0015	298031.60	233.6419	378.74	0.0019	272.22	0.1592
Reduced Temp	Reduced Press	Throat Dia.	ThrtPrss(Pa)	ThrtTemp(K)	ThrtVel(m/s)	TMssRt(kg/s)	NzStgTemp(K)	Inlet Dia.
4.5416	0.1625	0.0015	292895.03	480.8489	444.42	0.0016	573.15	#DIV/0!
4.3257	0.1463	0.0015	293401.48	481.9367	436.66	0.0017	573.15	#DIV/0!
1.8841	0.0748	0.0015	309571.28	517.1128	344.77	0.0020	573.15	0.0049
3.7957	0.1132	0.0015	268760.62	429.9915	386.12	0.0021	573.15	0.0038
0.8855	0.0250	0.0015	301006.52	498.3736	546.84	0.0013	573.15	0.0056
Reduced Temp	Reduced Press	Throat Dia.	ThrtPrss(Pa)	ThrtTemp(K)	ThrtVel(m/s)	TMssRt(kg/s)	NzStgTemp(K)	Inlet Dia.
6.1264	0.1625	0.0015	294952.61	654.6094	514.45	0.0014	773.1500	#DIV/0!
5.8351	0.1463	0.0015	295522.27	656.2652	505.41	0.0014	773.1500	#DIV/0!
2.5416	0.0748	0.0015	311915.07	704.5331	398.78	0.0017	773.1500	0.003305
5.1202	0.1132	0.0015	268760.62	580.0365	448.45	0.0018	773.1500	#DIV/0!
1.1944	0.0250	0.0015	303379.31	679.2509	632.58	0.0011	773.1500	0.003531
Reduced Temp	Reduced Press	Throat Dia.	ThrtPrss(Pa)	ThrtTemp(K)	ThrtVel(m/s)	TMssRt(kg/s)	NzStgTemp(K)	Inlet Dia.
13.2579	0.1625	0.0015	300243.70	1450.0232	750.21	0.0009	1673.1500	#DIV/0!
12.6275	0.1463	0.0015	300475.80	1451.4947	737.43	0.0009	1673.1500	#DIV/0!
5.5002	0.0748	0.0015	315352.49	1546.8892	583.05	0.0011	1673.1500	#DIV/0!
11.0805	0.1132	0.0015	268760.62	1255.2390	659.71	0.0012	1673.1500	#DIV/0!
2.5849	0.0250	0.0015	310727.26	1517.0027	918.83	0.0007	1673.1500	0.001220

1.6 N

Inlt Dnsty (kg/m^3)	Inlt Vlcty (m/s)	Inlet Mach No.	Exit Velocit	Thrust(N)	DschrgTime(s)
6.8446	4.5984	0.0137	752.4774	1.78546	6226.497433
7.0423	#DIV/0!	#DIV/0!	739.3758	1.78446	6399.777366
11.1982	1.4414	0.0056	667.1864	1.9342	0
9.7847	4.1339	0.0135	532.4399	1.6	7248.617252
999.9000	0.0001	0.0000	1006.0428	1.88089	90867.51535
			Exit Velocit	Thrust(N)	DschrgTime(s)
			1107.4414	1.80401	9069.499684
			1094.5834	1.8108	9336.494254
			1102.6177	2.15149	0
			772.5791	1.6	10517.8639
			1513.9441	1.93502	132916.4498
			Exit Velocit	Thrust(N)	DschrgTime(s)
			1313.8245	1.83261	10591.7486
			1299.8623	1.84102	10905.47618
			1338.6009	2.23425	0
			897.3062	1.6	12215.89465
			1815.1738	1.98467	155376.3461
			Exit Velocit	Thrust(N)	DschrgTime(s)
			2054.3499	1.92035	15805.01722
			2026.0568	1.92475	16258.57898
			2122.4488	2.385	0
			1320.0070	1.6	17970.528
			3007.7213	2.19061	233253.0561

0.2 N (~ 50 mlbs Thrust)

Gas	Strg Mss (kg)	NzInltTmp(K)	NzInltPrss(Pa)	NzInltR(J/(kg*K))	Nz Cp (J/(kg*K))	Nz k	KtcVsc(m^2/s)
Nitrogen	14.77	272.22	68947.00	296.8000	1040.0000	1.3994	1.906E-04
Air	15.45	272.22	68947.00	287.0000	1004.1000	1.4002	
Carbon Dioxide		272.22	68947.00	188.9200	817.6000	1.3005	9.952E-05
Argon	21.78	272.22	68947.00	208.1300	520.7000	1.6659	1.709E-04
Water	169.89	272.22	68947.00	461.5200	1859.0000	1.3303	
Gas	Strg Mss (kg)	NzInltTmp(K)	NzInltPrss(Pa)	NzInltR(J/(kg*K))	Nz Cp (J/(kg*K))	Nz k	KtcVsc(m^2/s)
Nitrogen	14.77	573.15	68947.00	296.8000	1069.9000	1.3839	
Air	15.45	573.15	68947.00	287.0000	1045.2000	1.3785	
Carbon Dioxide		573.15	68947.00	188.9200	1060.6000	1.2167	4.180E-04
Argon	21.78	573.15	68947.00	208.1300	520.7000	1.6659	6.305E-04
Water	169.89	573.15	68947.00	461.5200	1999.5000	1.3001	5.960E-04
Gas	Strg Mss (kg)	NzInltTmp(K)	NzInltPrss(Pa)	NzInltR(J/(kg*K))	Nz Cp (J/(kg*K))	Nz k	KtcVsc(m^2/s)
Nitrogen	14.77	773.15	68947.00	296.8000	1116.3000	1.3622	
Air	15.45	773.15	68947.00	287.0000	1092.7000	1.3562	
Carbon Dioxide		773.15	68947.00	188.9200	1158.8000	1.1948	0.0007
Argon	21.78	773.15	68947.00	208.1300	520.7000	1.6659	
Water	169.89	773.15	68947.00	461.5200	2130.8000	1.2765	0.0011
Gas	Strg Mss (kg)	NzInltTmp(K)	NzInltPrss(Pa)	NzInltR(J/(kg*K))	Nz Cp (J/(kg*K))	Nz k	KtcVsc(m^2/s)
Nitrogen	14.77	1673.15	68947.00	296.8000	1261.2000	1.3078	
Air	15.45	1673.15	68947.00	287.0000	1226.7000	1.3054	
Carbon Dioxide		1673.15	68947.00	188.9200	1346.2000	1.1632	
Argon	21.78	1673.15	68947.00	208.1300	520.7000	1.6659	
Water	169.89	1673.15	68947.00	461.5200	2703.4000	1.2059	4.479E-03

Reduced Temp	Reduced Press	NzStgTemp(K)	Inlet Dia. (m)	Inlt Dnsty (kg/m^3)	Inlt Vlcty (m/s)	Inlet Mach No.	ThrtDia(m)
2.1571	0.0203	272.2222	0.00122212	0.8538	296.1216	0.8807	0.0015
2.0545	0.0183	272.2222	#DIV/0!	0.8826	#DIV/0!	#DIV/0!	0.0015
0.8949	0.0093	272.2222	0.00182000	13.4771	10.3354	0.0400	0.0015
1.8028	0.0141	272.2222	0.00121055	1.2179	267.9740	0.8723	0.0015
0.4206	0.0031	272.2222	#DIV/0!	999.9000	#DIV/0!	#DIV/0!	0.0015
Reduced Temp	Reduced Press	NzStgTemp(K)	Inlet Dia.				Throat Dia.
4.5416	0.0203	573.1500	#DIV/0!				0.0015
4.3257	0.0183	573.1500	#DIV/0!				0.0015
1.8841	0.0093	573.1500	0.000614				0.0015
3.7957	0.0141	573.1500	0.000476				0.0015
0.8855	0.0031	573.1500	0.000689				0.0015
Reduced Temp	Reduced Press	NzStgTemp(K)	Inlet Dia.				Throat Dia.
6.1264	0.0203	773.1500	#DIV/0!				0.0015
5.8351	0.0183	773.1500	#DIV/0!				0.0015
2.5416	0.0093	773.1500	0.000414				0.0015
5.1202	0.0141	773.1500	#DIV/0!				0.0015
1.1944	0.0031	773.1500	0.000440				0.0015
Reduced Temp	Reduced Press	NzStgTemp(K)	Inlet Dia.				Throat Dia.
13.2579	0.0203	1673.1500	#DIV/0!				0.0015
12.6275	0.0183	1673.1500	#DIV/0!				0.0015
5.5002	0.0093	1673.1500	#DIV/0!				0.0015
11.0805	0.0141	1673.1500	#DIV/0!				0.0015
2.5849	0.0031	1673.1500	0.000153				0.0015

Appendix F

Corrosive Gases

Type	Composition, vol%					Typical Dew Point	
Reducing Atmospheres	N_2	CO	CO_2	H_2	CH_4	C°	F°
Exothermic unpurified	71.5	10.5	5.0	12.5	0.5	+27	+80
Exothermic purified	75.3	11.0	. . .	13.0	0.5	-40	-40
Endothermic	45.1	19.6	0.4	34.6	0.3	+10	+50
Charcoal	64.1	34.7	. . .	1.2	. . .	-29	-20
Dissociated ammonnia	25	. . .	. . .	75	. . .	-51	-60
Carburizing Atmospheres							
Endothermic+Hydrocarbon *	. . .	. . .	. . .	. . .	. . .	. . .	. . .
Endothermic+Hydrocarbon+ammonia *	. . .	. . .	. . .	. . .	. . .	. . .	. . .

* No standard composition

Source: ASM Metals Handbook, 1983.

Appendix I

Materials Selection

SELECTION CRITERIA DEVELOPMENT

Properties

1. Mechanical
    a. Creep
    b. Wear
2. Physical
    a. Electrical
    b. Conduction
    c. Melting Point
3. Chemical
    a. Conduction

Available

1. Minimum order requirement
2. Special processing required

Economics

1. Quantity required
2. Anticipated service life
3. Fabricability

PARTS LISTS

1. Nozzle
2. Heating element
3. Heating element insulation
4. Heat exchanger
5. Heat shields
6. Mounting devices
7. Mounting insulation
8. Casing
9. Power leads
10. Gas Lines

Other: Coatings, gaskets, mounting, interfaces

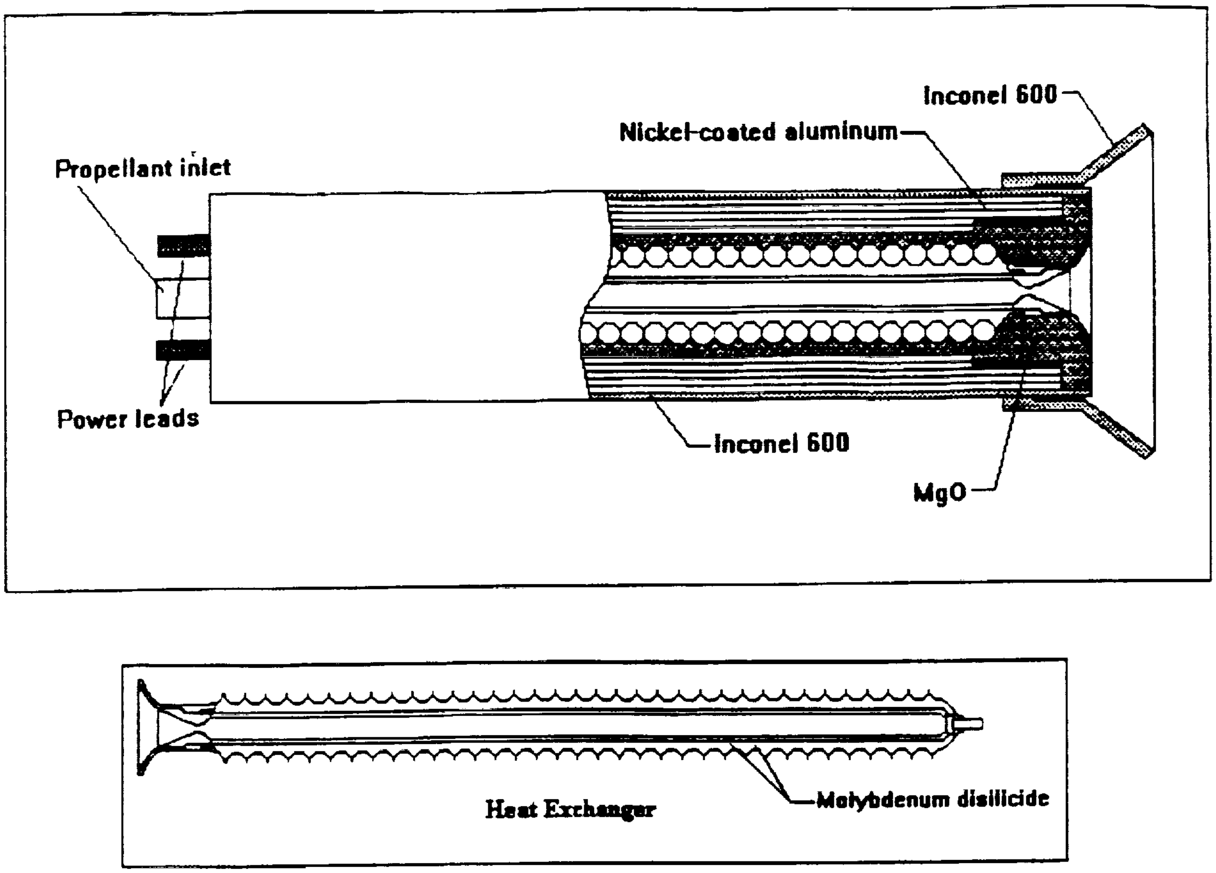


Figure 1. Heater configuration. The system consist of functional elements of a coupled resistive heater coil and heat exchanger. This design is one that was modified by incorporating the $MoSi_2$ sheath for corrosion resistance.

Appendix J

Heating Apparatus

This appendix presents the analysis of the heating coil. To insure that the heating element does not short the platinium-rehdinium coil be protected by an insulating material. The platinium-rehdinium wire will be coated with a layer of MgO ceramic. Further analysis is necessary to specify the subsquent length of the coil and the diameter of the $MoSi_2$ wire. From the previous data based on resistojets, the analysis is avaliable. The minimum diameter of the wire is related to the current I through the wire and the resisitivity of the material:

$$(d_{wire})_{min} = \left(\frac{4I^2 \rho_w}{\pi^2 q_{cr}}\right)^{1/3}$$

Where ρ_w is the resistivity of the heating alloy. From this prespective, the design of the heater is reduce to the optimization of the diameter and the heat transfer. The heat transfer is is quantatified by the exchange of thermal energy between the propellant heat exchanger and the heater current/voltage options. The amount of the power dissapated per unit length (P/l) is:

$$(P/l) = \left(\frac{4I^2 d\rho_w/dT}{\pi d_w}\right)^{T_w}$$

The heater length L decreases as the quantity of the heater current divided by the heater diameter (I/d_w) decreases for a fixed power. If the heater wire temperature (T_w) increase can be assumed to be linear, then the heater length is approxiamately:

$$L = (\pi P)_{/2} (d_w/I) \left(\frac{1}{(\rho^w/T)(T_{max} + T_{in})}\right)^{T_w}$$

The resulting dimensions is contained in the following table.

Table 1.

Heater Coil Calculations Data

Known conditions	Value
Power	500 W
Current	35 Amps
Maximum Heater Temperature	1670° K
Terminal Temperature	400° K
Calculations	Value
Diameter	0.060 in
Heater Length (Coil)	78.7 in

Source: Purmire, p.3-5.

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