DESIGN ANALYSIS OF LEVITATION FACILITY FOR SPACE PROCESSING APPLICATIONS

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FINAL REPORT

15 NOVEMBER 1974

Contract No. NAS8-29680, Modification No. 3

Prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Process Engineering Laboratory
George C. Marshall Space Flight Center

SPACE SCIENCES LABORATORY
GENERAL ELECTRIC
SPACE DIVISION

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FOREWORD

The final report on Contract NAS8-29680 dated 13 May 1974 reviews a wide spectrum of materials and processes which are candidates for containerless processing experiments which can potentially lead to new scientific knowledge or to potentially new and improved materials. This work also delineates the facility requirements for carrying out such experiments and processes within probable Space Laboratory constraints and emphasizes the environment which must be provided to the specimen being processed in terms of environmental gas or vacuum, method of heating and melting, required intensity and frequency of applied electromagnetic fields used for positioning and heating and the coil configurations required to provide such fields. Rough estimates of achievable electrical efficiencies for providing these heating and positioning fields were made in order to discuss limitations and specimen sizes and melting temperatures for several assumed Space Laboratory peak power capabilities. Current NASA system engineering studies which are being or will be carried out in order to define the materials processing missions and payloads require a more detailed consideration of the equipments suitable for incorporation in Spacelab and Shuttle pallet payloads in order to provide detailed payload configurations and groupings, to define equipment development and engineering problems and to define in more detail the main interfaces with the carrier vehicles, particularly in regard to electrical power sources and power conditioning, heat rejection, and command, control and telemetry. Because this effort was carried out concurrently with the Bendix study on Automated Space Processing Payloads, Shuttle pallet requirements are emphasized. It should be pointed out, however, that most experiments which can be considered for the Spacelab can also be considered for the Shuttle pallet with the exception that a dedicated Space Shuttle could carry additional facility modules for performing a wider range of experiments and processes on a single flight.

SUMMARY

The work described in this report represents a continuation of the work under Contract NAS8-29680 which was summarized in the final contract report dated 13 May 1974. This report covers the work done on this contract extension, designated as Modification No. 3, for the purposes of further defining containerless processing facilities for the Space Laboratory and Space Shuttle, and in particular to serve as inputs to the concurrent Automated Space Processing Payloads Study, Contract NAS8-30741, by the Bendix Aerospace Systems Division. Four materials process examples were chosen as representative of those delineating the most severe requirements for the facility in terms of electrical power, radio frequency equipment and the use of an auxiliary electron beam heater and were used as the framework to discuss matters having the greatest effect upon the Space Shuttle pallet payload interfaces and envelopes. One of the examples chosen, alumina, will require acoustic or other non-electromagnetic positioning techniques. Although the very limited scope of the study did not allow a detailed consideration of the many other processes described in the Contract NAS8-29680 final report, it is believed that the examples chosen represent extremes with respect to electrical power requirements, heat rejection requirements and electrical equipment development. Sufficient engineering was done to derive significantly improved weight, volume and efficiency estimates for the RF generating equipment. Previous estimates by other contractors based upon commercially available equipment operated from 60 cycle power sources have been refined to take account of the substantial improvement in electrical efficiency to be achieved utilizing modern high frequency inversion techniques starting from DC bus power. These results are particularly significant because of the resulting reduced requirements for heat rejection from electrical equipment which, at present, appears to be one of the principal envelope problems for shuttle pallet payloads.

Considerable additional work is also reported on typical specimen temperature and electrical power versus time profiles. This work shows that although

experiments on containerless melting of high temperature refractory materials will make it desirable to consider the highest peak powers which can be made available on the pallet, total energy requirements are kept relatively low by the very fast processing times typical of containerless experiments and allows consideration of heat rejection capabilities lower than peak power demand if energy storage in system heat capacitances is considered. The use of batteries can also be considered to avoid a requirement for fuel cells capable of furnishing this brief peak power demand.

1. PROCESS EXAMPLE SELECTION

1.1 RATIONALE

The rationale used to select the process examples was based upon the need to represent a broad range of materials and processes which might be flown on shuttle or shuttle pallet missions by a few typical cases to be studied in further depth. The following factors were considered in selecting these examples.

(1) Temperature. Some widely different melting points must be selected to reflect the wide range of temperatures which will be required for the total spectrum of experiments under consideration at the present time.

(2) Electrical resistivity. The range of resistivities to be considered at the present is from very good conductors to insulators. This influences the type of positioning that may be employed (electromagnetic or acoustic), the type of heating, and in the case of induction heating, the efficiency of heating.

(3) Coefficient of secondary electron emission. This determines the ability of a specimen of the material to be electron beam heated and melted while freely floating.

(4) The environment of the specimens. The environmental requirements will vary from high vacuum to an inert or active gas pressure of one atmosphere. This affects the positioning technique and the heating technique to be employed. For example, acoustic positioning cannot be employed where a high vacuum is required nor can electron beam heating be applied when the total pressure exceeds a few torr.

(5) Type of process. Processes considered are purification and grain refinement, dispersed phase alloys, and glass production.

In light of the above criteria, four process examples were considered which represent extremes from the point of view of range of equipment requirements. These were:

(1) Tungsten - purification and grain refinement. The metal tungsten is a high melting point ($3410^{\circ}C$), good conductivity (5 microohm-cm at $20^{\circ}C$), high coefficient of secondary electron emission (for beam energies > 3 kev) metal. The process of purification and grain refinement through heating, degassing, melting, supercooling and nucleation at a high degree of supercooling requires a vacuum of 10^{-5} torr or better. Electromagnetic, but not acoustic, positioning may be employed for this process. Because of its high melting temperature, electron beam heating and melting is favored and the high coefficient of secondary electron emission makes this feasible.

(2) Beryllium - dispersion of beryllia in beryllium. The metal beryllium has a low melting point ($1282^{\circ}C$), good conductivity (5.5 microhm-cm at $20^{\circ}C$) and a low coefficient of secondary electron emission. The dispersion process may be carried out either in a very pure inert gas or a vacuum of 10^{-5} torr or better. Because of its low melting temperature, and low coefficient of secondary electron emission, it is a candidate for induction heating. Because of its high conductivity it is an ideal candidate for electromagnetic positioning using relatively low radio frequencies and has a low but acceptable efficiency for induction heating.

(3) Zirconia - glass production. Zirconia has a high melting point ($2715^{\circ}C$), poor conductivity at room temperature, high coefficient of secondary electron emission. At $2000^{\circ}C$, however, its electrical resistivity is 10^{-2} ohm meters. Preheated to this temperature, it is a candidate for electromagnetic positioning. Thus, either electromagnetic or acoustic positioning may be used. The glass making process may require

an active gas environment such as oxygen. Hence, induction heating is favored because of its high efficiency for the processing (after preheating and insertion). This process example may either employ electromagnetic or acoustic positioning.

(4) Alumina - glass production. Alumina has a high melting point (2050°C), poor conductivity and high coefficient of secondary electron emission. When molten its resistivity is not below 10^{-2} ohm meters. Thus, it is not a candidate for electromagnetic positioning but is for acoustic positioning. Since the process may use an active gas environment such as oxygen, this is feasible. A resistance oven, thermal imaging, or a muffle furnace may be considered for heating.

2. PROCESS TIME LINES

2.1 TEMPERATURE KINETICS

The following development, through eq. (5) is essentially as given in the earlier report but is repeated as an introduction to the additional development which follows. The time to melt a spherical specimen with a given amount of power supplied to the specimen for heating and melting can be estimated by considering the power balance equation given by

$$N - A\sigma\epsilon T^4 = mC\frac{dT}{dt} \tag{1}$$

for heating to the melting point. This equation states that the power supplied for heating minus the losses due to radiation equals the actual power absorbed by the material in raising the temperature. This equation can be put into the form

$$dt = \frac{\beta}{\alpha}\left\{\frac{d\mu}{(1-\mu)^4}\right\} \quad \text{with } \mu = \alpha T. \tag{2}$$

Here

$$\beta = \frac{mC}{N}$$

$$\alpha = \left(\frac{A\epsilon\sigma}{N}\right)^{1/4}$$

C = the specific heat of the metal

N = the power supplied for heating

A = the surface area of the body

ϵ = the emissivity of the body

σ = Stefan's constant.

Taking the specific heat to be the average specific heat over the temperature range between room temperature and melting and the power supplied to be constant, Equation (2) may be integrated to obtain

$$t_1 = \frac{\beta}{2\alpha}\left\{\tan^{-1}(\alpha T_m) + \tanh^{-1}(\alpha T_m)\right\} - \frac{\beta}{2\alpha}\left\{\tan^{-1}(\alpha T_1) + \tanh^{-1}(\alpha T_1)\right\} \tag{3}$$

where t_1 is the time to reach the melting temperature T_m from the initial temperature T_1, which may be room temperature or some preheating temperature.

In order to melt the specimen, an additional amount of heat mL must be supplied to the body and the time necessary to supply this heat is given by

$$t_2 = \frac{mL}{N - A\epsilon\sigma T_m^4} \tag{4}$$

where m is the mass of the body and L is the latent heat of fusion. The total time, then, to heat and melt the body is given by

$$t = t_1 + t_2 \tag{5}$$

The basic physical assumptions used to develop the equation are that the body is heated uniformly so that it experiences a corresponding temperature rise throughout its volume and that the power supplied to the body is constant. Considerations of heat flow have been neglected. For small specimens where heat can be transferred rapidly throughout the specimen, this is a good assumption and the developed equation is a good estimate.

It is clear that, to melt at all, the power supplied, N, must be greater than the power radiated at the melting temperature, $A\epsilon\sigma T_m^4$. For values of $N \approx A\epsilon\sigma T_m^4$, it will take extremely long times to melt the specimen. If there is convective heat loss beside the radiated heat loss, the time must rise additionally. For the specimen in a vacuum chamber in the weightless environment or in a chamber filled with inert gas, it is reasonable not to consider convective losses which would occur in the one gravity environment.

If heating power $N > A\epsilon\sigma T_m^4$ continues to be supplied to the specimen after melting, the time required to heat to temperature T_f is

$$t_s = \frac{\beta_1}{2\alpha_1}\left\{\tan^{-1}(\alpha_1 T_f) + \tanh^{-1}(\alpha_1 T_f)\right\} - \frac{\beta_1}{2\alpha_1}\left\{\tan^{-1}(\alpha_1 T_m) + \tanh^{-1}(\alpha_1 T_m)\right\} \quad (6)$$

with

$\beta_1 = \dfrac{m\,C_1}{N}$

$\alpha_1 = \left(\dfrac{A\,\epsilon_1\,\sigma}{N}\right)^{1/4}$

C_1 = the specific heat of the liquid metal

ϵ_1 = the emissivity of the liquid metal

T_f = the final temperature

T_m = the melting point

Cooling curves from the temperature above the melting point down to the nucleation temperature can be plotted using the equation

$$t = \mu \left\{ \frac{1}{T_n^3} - \frac{1}{T_f^3} \right\} \tag{7}$$

where

$\mu = \dfrac{\rho_g V C_l}{3 A \epsilon_l \sigma}$

T_n = the temperature at which nucleation is initiated

ρ_g = the density of the liquid metal

V = the volume of the melt

A = the surface area of the melt.

From the developed theory of homogeneous nucleation $T_n \approx 0.82\ T_m$. Equation (7) is developed from the principle that the rate of heat loss from the bulk melt is equal to the rate of heat radiated from its surface or

$$-\rho_g V C_l \frac{dT}{dt} = A \epsilon_l \sigma T^4. \tag{8}$$

The solidification time of the melt, after nucleation, is a very complicated problem. It is possible, however, to obtain an upper and lower bound for solidification times by relatively simple calculations. The lower bound on solidification time would be if the melt all solidified at the melting temperature T_m. This can never occur in principle because the nucleation rate is zero at the melting temperature. Some supercooling, however slight, must occur to initiate nucleation. The upper bound on the solidification time would be if the melt all solidified at the nucleation temperature, T_n. This can never occur in principle because the release of latent heat of fusion at the crystal-melt interface must raise the interface temperature above the nucleation temperature, T_n.

Thus we can bound the solidification time between an upper bound time given by

$$t_{U.B.} = \frac{\rho_g VL}{A\epsilon\sigma T_n^4} \tag{9}$$

and a lower bound time given by

$$t_{L.B.} = \frac{\rho_g VL}{A\epsilon\sigma T_m^4} \tag{10}$$

Somewhere between these times is the actual solidification time, which would require a very complicated mathematical analysis to obtain.

2.2 TEMPERATURE KINETICS PROGRAMS

Several programs have been written to implement the temperature-kinetic calculations discussed above. The first program written examines the heating and melting of specimens. Using equations (3) and (5), it has the following capabilities:

(1) A temperature-time profile incorporating an arbitrary number of dwells in the solid state at arbitrary temperatures below the melting point and a dwell in the liquid state. Powers applied can be varied to reach different dwell temperatures and the program will not run if insufficient input powers are applied.

(2) Power-time profiles giving the power applied while heating to a dwell temperature and the power required during a dwell in the solid or the liquid state.

(3) Energy accumulated versus time profiles so that the energy required for the heating and melting and the heat rejection problem can be studied. These profiles are automatically plotted by the computer graphics section so that the entire job is performed by the computer.

The second program written is a modification of the first program. It essentially uses Equations (3) and (4) instead of (5), separating out the time to melt from the time to heat to the melting temperature. This program is used to study whether the limiting factors are time to reach melting temperatures or time to furnish the latent heat of fusion.

The third program solves the problem of what power is required to reach a dwell temperature or the melting point in a specified time. This program can be used when the required times are known but the powers required are not.

The fourth program is used to study the entire process of heating, melting, supercooling and solidification. It makes use of (3), (4), (6), (7), (9) and (10) to generate a temperature-time profile for the entire process of heating, dwelling at selected temperatures, melting, superheating, dwelling at superheated temperatures, supercooling and solidification (upper bound and lower bound estimates). Arbitrary powers, dwell temperatures, dwell times, times to superheat, and material parameters such as specific heat for solid and liquid phases can be used as inputs. This is a very useful program which may be used to study such processes as grain refinement and purification of metals, making dispersed phase alloys, glasses, etc.

2.3 PROCESS TIME LINES CONSIDERED

A number of representative process time lines were studied for each of the following processes

(1) purification and grain refinement of tungsten

(2) beryllium with a dispersed phase of beryllia or purification and grain refinement in beryllium

(3) amorphous transparent zirconia

(4) amorphous transparent alumina.

Using the first program written, heating and melting time line profiles were considered for the four processes, varying such parameters as dwell temperature, dwell time, specimen size, applied power where it was considered appropriate.

Five cases were considered for tungsten. These are summarized in Table 2-1. Since, even with 10,000 watts of available power for heating and melting, the maximum radius specimen that can be melted is 1.31 centimeters, we should consider this maximum to obtain useful test specimens. Assuming, then, that radius and 10,000 watts of applied power, possibly through the use of an electron beam for melting, a variety of temperatures and times for dwell in the solid state and various lengths of dwell in the liquid state were chosen. These dwells are required for solid state degassing and liquid state degassing before supercooling the melt. The dwell temperatures taken were 2400°C, 3200°C and 3400°C (molten). Dwell times were varied from 5 to 10 minutes in the solid state and 2 to 5 minutes in the liquid state. The applied powers were 3500 watts to reach 2400°C, 8600 watts to reach 3200°C, and 10,000 watts to melt at 3400°C. With these applied powers it took 23.16 seconds to reach 2400°C from 20°C, 5.9 seconds to go from 2400°C to 3200°C and 49.18 seconds to go from 3200°C to the liquid state at 3400°C. During the dwell at 2400°C the tungsten will radiate a power of 2496 watts, 7113 watts at 3200°C, and 8996 watts at 3400°C. The lowest accumulated energy was for the first process time line with one ten minute dwell at 2400°C and a 2 minute dwell molten, while the highest was the fifth process time line with a 10 minute dwell at 2400°C, a ten minute dwell at 3200°C, and a 5 minute dwell molten. These were 3.191×10^6 watt-seconds and 0.089×10^6 watt-seconds respectively. The

Table 2-1

Process Time Line	Radius (cm)	1st Dwell Temp. (^oK)	1st Dwell Time (sec)	2nd Dwell Temp. (^oK)	2nd Dwell Time (sec)	3rd Dwell Temp. (^oK)	3rd Dwell Time (sec)	Total Time (sec)	Max. Pwr (watts)	Total Energy (watt-sec)
Tungsten										
1	1.31	2673	600	3683	120			796.43	10^4	3.191×10^6
2	1.31	2673	300	3473	300	3683	120	798.24	10^4	4.587×10^6
3	1.31	2673	600	3473	600	3683	120	1398.24	10^4	7.470×10^6
4	1.31	2673	300	3473	300	3683	300	978.24	10^4	6.206×10^6
5	1.31	2673	600	3473	600	3683	300	1578.24	10^4	9.089×10^6
Be										
1	3.5	1273	300	1557	120			2407.01	3×10^3	3.727×10^6
3	3.5	1273	300	1557	300			2587.01	3×10^3	4.096×10^6
9	3.5	1273	300	1557	120			1026.79	4×10^3	2.655×10^6
19	2.0	1273	120	1557	60			410	2×10^3	3.8×10^6
18	3.5	1273	300	1557	300			763.76	10^4	2.527×10^6
ZrO_2										
3	1.5	2788	300	2988	120			451.53	10^4	2.533×10^6
4	1.5	2788	300	2988	300			631.53	10^4	3.683×10^6
6	1.0	2788	300	2988	300			606.48	10^4	1.563×10^6
Al_2O_3										
2	3.0	2100	300	2323	300			1483.95	10^4	13.510×10^6
4	2.0	2100	300	2323	300			658.85	10^4	2.664×10^6

The powers and total energies given here and in Figures 2-1 through 2-8 refer to specimen heating alone. Separate account will be taken later of total facility power requirements.

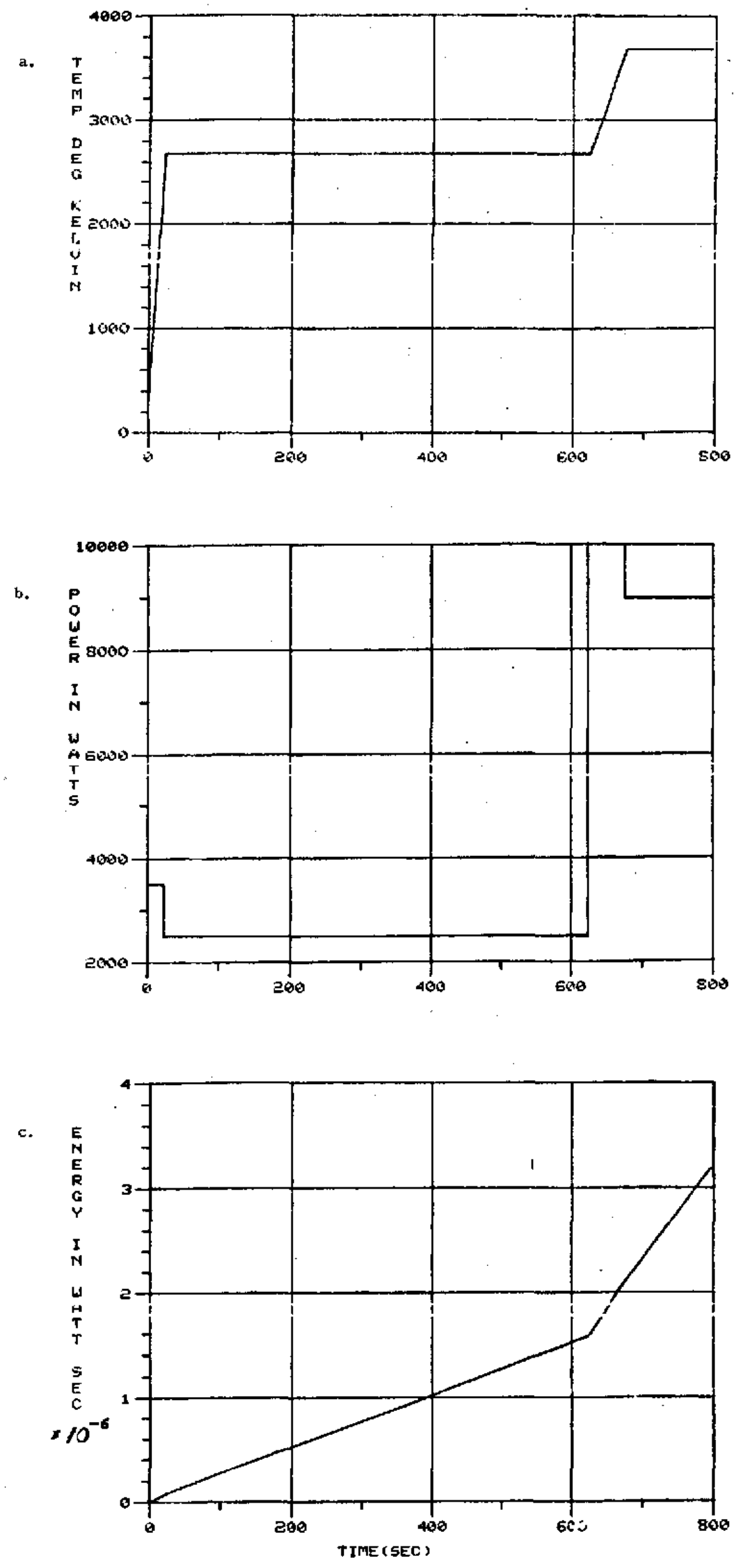


Figure 2-1. Tungsten First Process Time-Line

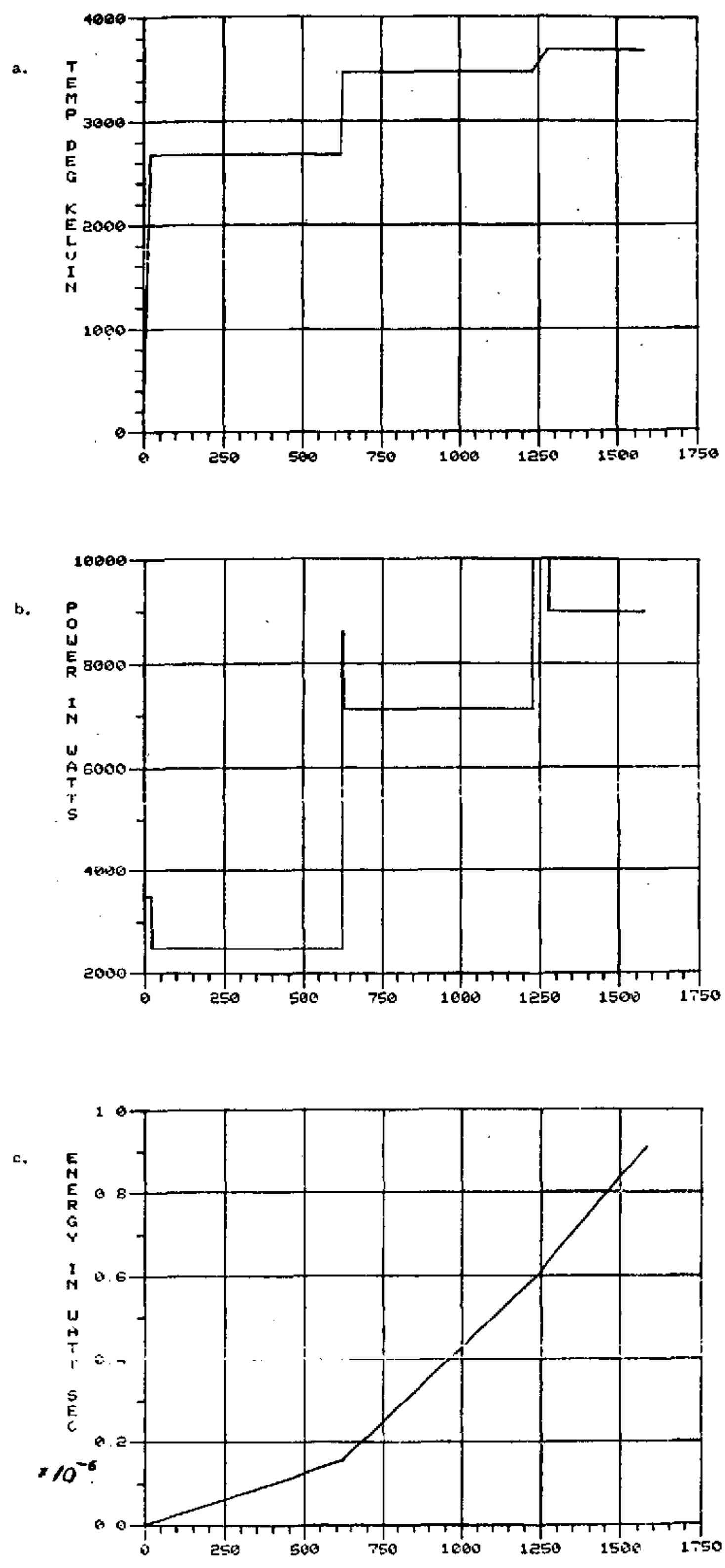


Figure 2-2. Tungsten Fifth Process Time-Line

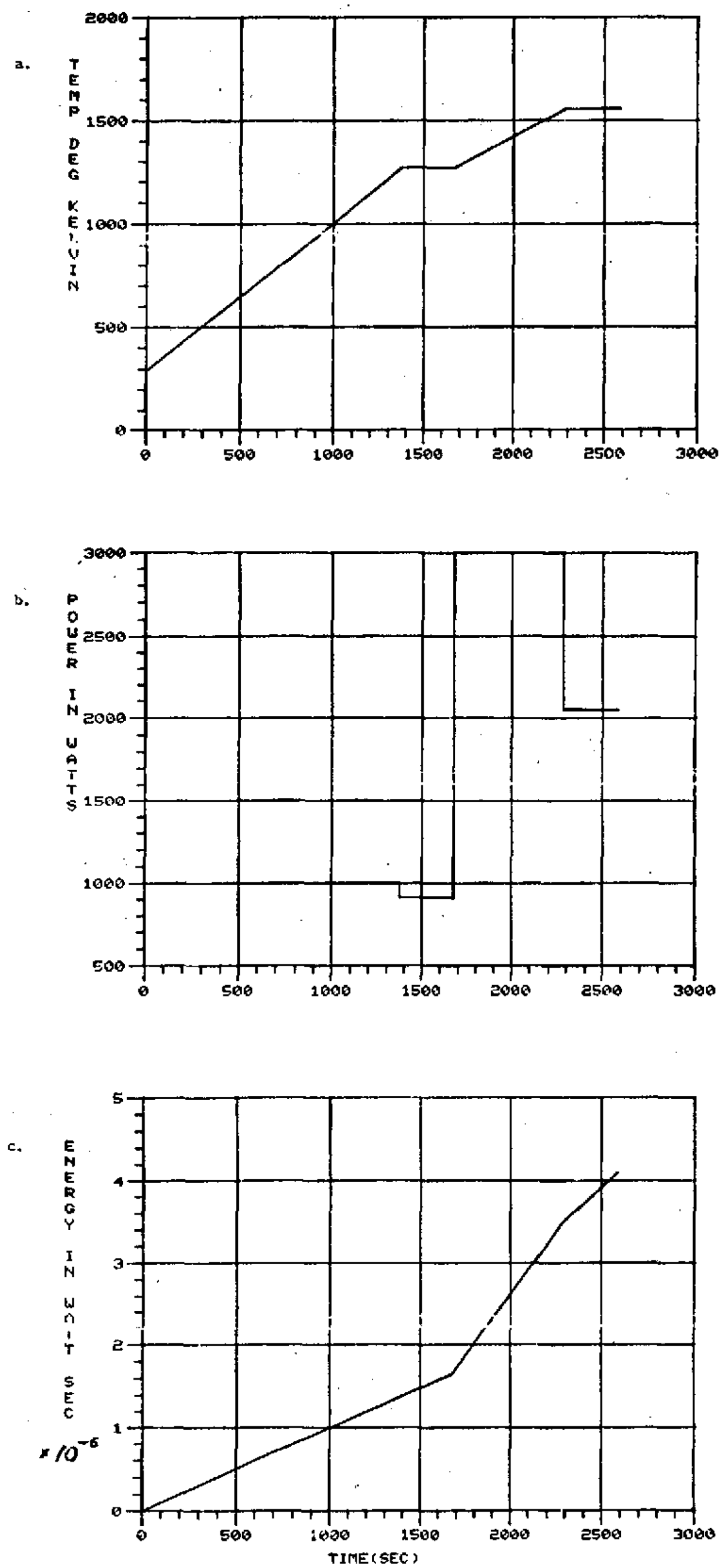


Figure 2-3. Beryllium Third Process Time-Line

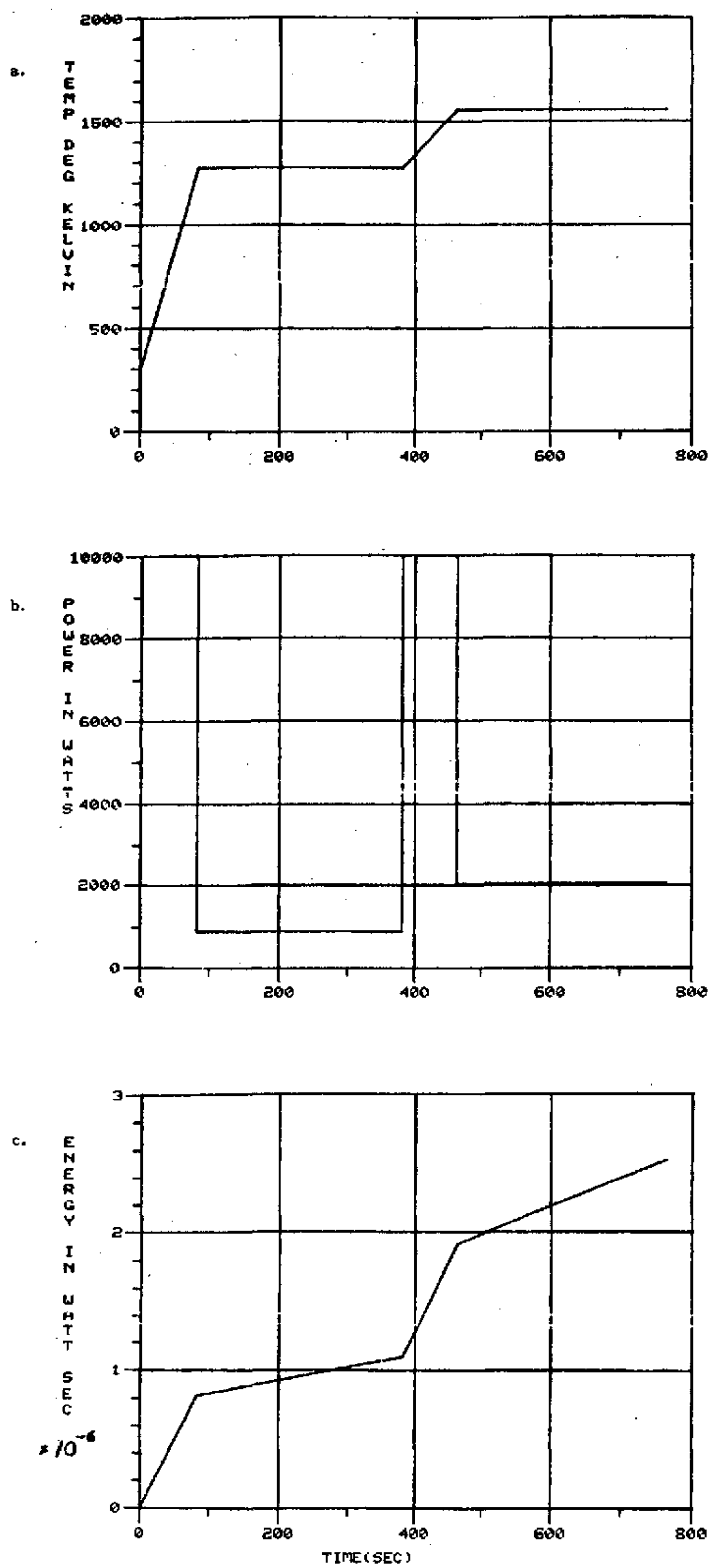


Figure 2-4. Beryllium Eighteenth Process Time Line

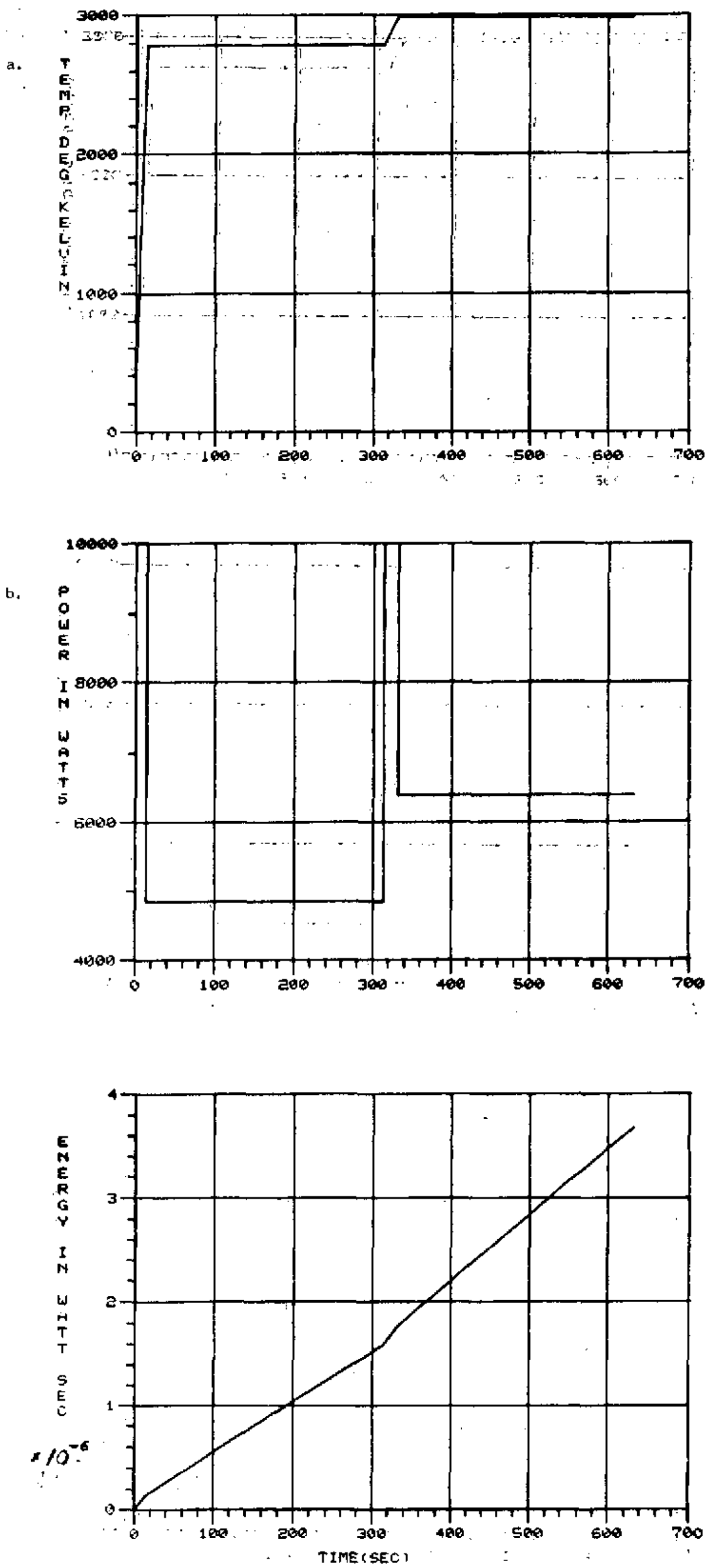


Figure 2-5. Zirconia Fourth Process Time-Line

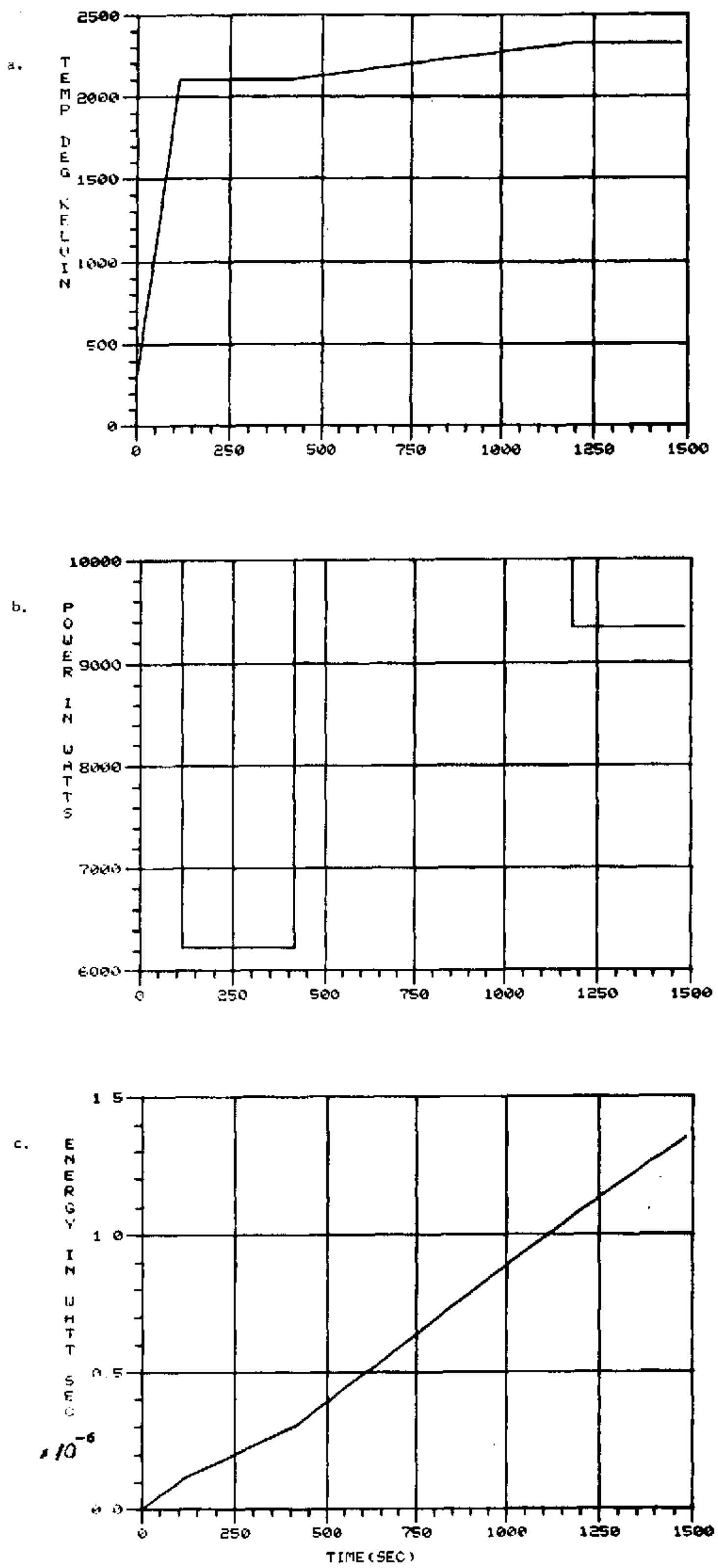
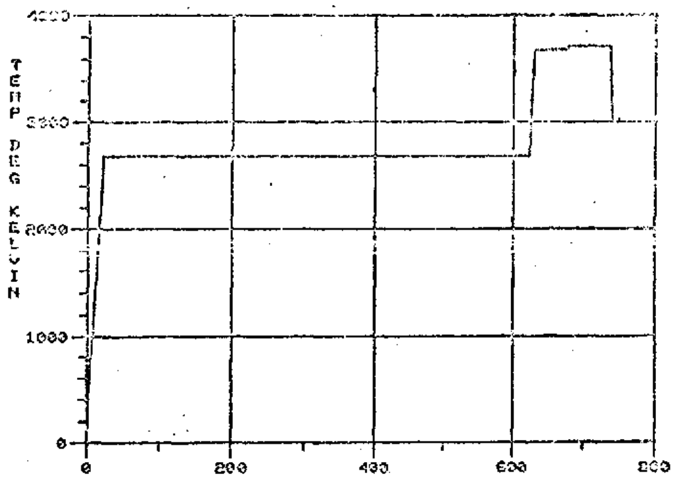
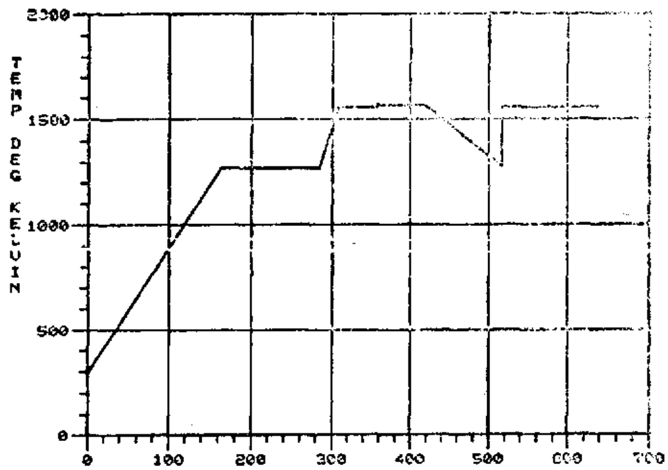


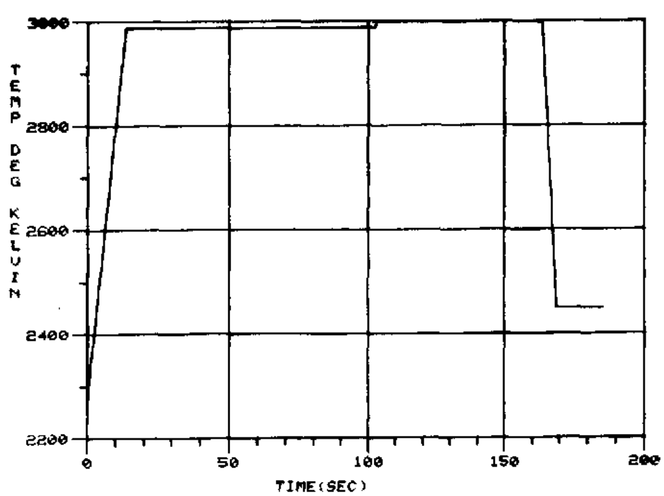
Figure 2-6. Alumina Second Process Time-Line



a. Tungsten Upper Bound Time-Line (Power=3500, 10000 W) (Radius=1.31cm)



b. Beryllium Lower Bound Time-Line (Power=1000, 2300 W) (Radius=2.0 cm)



c. Zirconia Upper Bound Time-Line (Power=5200 W) (Radius 1.3 cm)

Figure 2-7. Example of Heating, Melting and Radiative Cooling Calculations time line profiles are shown below for these cases (Figures 2-1 through 2-2). Process time may vary just for heating, degassing and melting from 796.43 seconds to 1578.24 seconds.

With beryllium, specimen radii of 3.5 and 4.0 centimeters were chosen and specimen powers were selected as 3000, 4000 and 10,000 watts. Dwell temperatures of 1000°C and 1284°C (molten) were chosen and dwell times solid of 5 and 10 minutes and dwell times molten of 2 and 5 minutes were chosen. Powers to reach the solid state dwell were chosen to be 1000 watts, 2000 watts, 3000 watts and 10,000 watts. The third process time-line and the eighteenth are shown in Figures 2-3 through 2-4. It is evident here that the higher power applied for the eighteenth process time line decreased the accumulated energy through considerably shortening the time to reach the solid state dwell and to subsequently melt the specimen from that temperature. Table 2-1 summarizes other cases.

A process time line for heating and melting zirconia is shown in Figure 2-5 and for alumina in Figure 2-6. The maximum size for zirconia with 10,000 watts specimen power was found to be 1.5 centimeter radius and for alumina, 3 centimeters radius. With the requirement of an active gas environment such as oxygen for processing these glasses and, in the case of alumina, the heating power cannot be furnished through electron beam heating for acoustic positioning.

Using the fourth program written, a number of complete process time lines were studied for tungsten, beryllium and zirconia. Examples of each are presented in Figure 2-7. The zirconia was treated as if it crystallized, whereas the desire for the process is to produce amorphous zirconia. The fictive temperature range for zirconia glass is not at the present time known. It would lie somewhere below the homogeneous nucleation temperature. Therefore, to estimate the glass forming time for zirconia, it was assumed to lie near the upper bound curve for solidification. More exact calculations for transparent oxide glasses require filling critical knowledge gaps by experimental work.

2.4 LIMITATIONS

The mathematical programs described assume that the quantities N, ϵ and C are constants, or at least do not vary much over the temperature interval involved in any given process step. The radiated power varying as the fourth power of the temperature is by far the most important change in the terms in Equation (1) as the specimen is heated. We shall discuss here variations in the specimen input power N, its surface emissivity ϵ and its heat capacity C. We shall also discuss how the programs just described can be used to do calculations where these variations can be taken into account if so desired.

As the specimen is heated, its electrical resistivity will change and, hence, the eddy currents induced from a fixed amplitude alternating field will change. For the metals and alloys, the electrical resistivity may typically increase by an order of magnitude in going from room temperature to the molten state. In Section 4 of Reference 1, the relation between heating efficiency and specimen resistivity was discussed. For oxides and semiconductors, the resistivity will drop rapidly with increase in temperature. Some of these materials, such as zirconia, may be preheated prior to release into the containerless processing facility. The further reduction in resistivity of these materials as they are further heated to melting may be only on the order of one decade. This analysis shows that for the practical operating situation, the heating efficiency will increase as the square root of the specimen resistivity in the regime of interest. In view of these typical variations, we expect the heat input N to the specimen to change by the order of a factor 2 or 3 for most processes considered. This is a small change compared to the very large change in the radiative term but is nevertheless important.

The emissivity ϵ is also expected to change with temperature, particularly as the surface condition of the specimen may change due to migration or outgassing of impurities. A drop in emissivity may also occur as some specimens with rough surfaces become molten. The changes again are much less important than the T^4 Stefan Boltzman factor but should be taken account of, where known. The heat capacities also change with temperature as the solids are heated. Examination of specific heat capacities for transition from solid to liquid phase of some common metals such as aluminum, copper, gold and iron shows that while the change is abrupt, it is also small and for first estimates can be neglected. This is shown in Figure 2-8. The change from the solid Fe phase to liquid Fe is not given on this figure but is from 10.5 calories/degree-mole to 10. The solid phase changes in iron give higher values of change than this. For the metals considered, tungsten and beryllium, the change in specific heat capacity at the melting point can be neglected without consequential error in computations. This is important, for in many cases, the transitional data has not been measured.

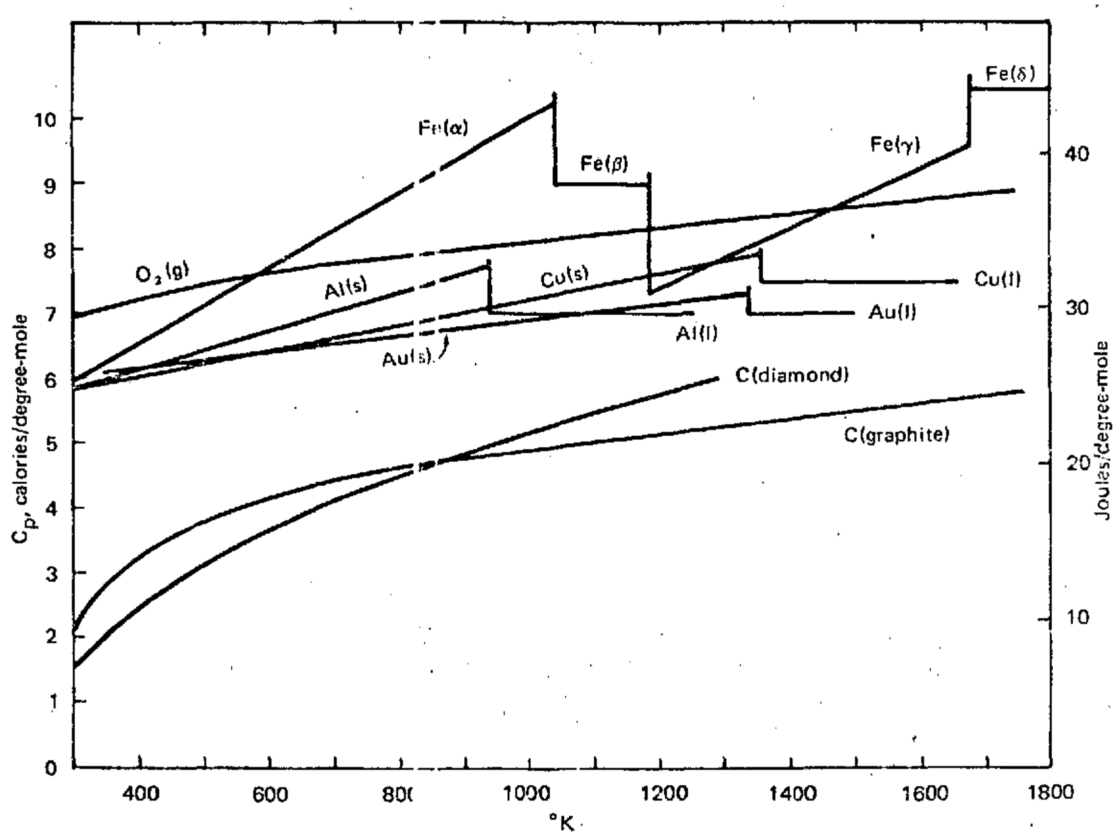


Figure 2-8. The Constant-Pressure Molar Heat Capacities of Several Elements

Since the precision required in estimating processing times is not great at this point, it is inappropriate to introduce detailed functional dependence of the "constants" of Equation (1) into an integration routine. Rather, it is more appropriate to utilize appropriate averages obtained by quick inspection of the graphs or other data and to use the kinetics programs already described. If a given temperature range is divided into several sub-ranges, appropriate averages of the constants within each range can be introduced to compute the heating times separately for each range. It is considered that generally the available data would not justify utilizing more than 2 or 3 ranges, except possibly for intrinsic semiconductors where the resistivity variation with temperature would be extreme.

3. PROCESSING REQUIREMENTS

3.1 SPACE PROCESSING REQUIREMENTS

The requirements for processing these materials have been determined and are given in Reference 1. Some special considerations have to be given to the use of the pallet on the space shuttle. It appears likely, because of various constraints on pallet payloads, that the principal objectives of the experiments will be the scaling up of work done in sounding rocket flights or for performing new experiments incompatible with the sounding rocket -- not in pilot plant space processing. For the pallet, sizes of specimens are likely to be larger than what could be handled on the ground or in sounding rocket experiments but not as large as the expected amount for space processing. A very important factor in specimen size is the heat rejection problem during the experiment. This in itself may be the limiting factor to specimen size.

Specific requirements for each of the products discussed in Section 3.1 include:

(1) The method of sample insertion into the containerless processing facility. The methods considered are mechanical and electromagnetic. For the space pallet, however, the chosen method of insertion was mechanical.

(2) The heating profile, including periods of maintaining required temperatures. A process to produce tungsten with enhanced service properties for medical x-ray targets, for example, requires at least two dwell periods for vacuum purification of commercial grade materials.

(3) The process environment, which might be vacuum, inert gas, or active gases, and the processing facility.

(4) The maximum temperature required. Extremes are tungsten at a melting temperature of 3420°C and beryllium, correspondingly, 1300°C.

(5) The necessity, where required, for preheating the material before insertion into the containerless processing facility. Many materials, such as zirconia, have high electrical resistivities at room temperatures which preclude electromagnetic position control at room temperatures. Preheating zirconia by an electron beam or resistance oven above 2000°C, however, decreases the electrical resistivity to 10^{-2} ohm meters and so enables preheated specimens to be positioned by electromagnetic forces in the containerless processing facility.

(6) Required cooling rates. These are established either for free radiation cooling or for quenching. Typically, cooling rates of 1000°C/sec. might be obtained by quenching for high temperature materials such as tungsten, while rates substantially less than this, e.g. 100°C/sec., might be obtained for free radiation cooling of more typical materials. For controlled cooling, where the power is reduced slowly, rates of less than 10°C/sec. may be obtained. The types of quenching considered were gas quench at 70°F, liquid at 70°F, or a cryogenic quench at much lower temperatures, such as that of liquid nitrogen.

(7) Heating power required. This could vary from as little as one kilowatt for small specimens to the maximum assumed Pallet or Spacelab power of 20 kw.

(8) The method of product recovery, which was selected to be mechanical based on consideration of overall simplicity.

(9) Process duration. This includes time to melt, time spent for dwell periods, time molten, and cooling time.

(10) Waste produced; including gaseous products, liquid products, solid products, and heat.

(11) Process safety requirements. Safety considerations, for example, consider the hot product, the presence of reactive product gases, liquids or solids; the presence of particulate radiation, such as secondary electrons from electron beam heating; or electromagnetic radiation, which may be x-ray, γ-rays, ultra-violet, optical, infrared, and radio frequency. Tungsten, for example at 3410^{o}C, cannot be directly observed without risk of damage to the eye.

3.2 AUTOMATION CONSIDERATIONS

The principal processing steps requiring automation are the following

(1) Sample insertion and recovery

(2) Heating power and temperature control

(3) Vacuum or inert gas partial pressure control

(4) Specimen quenching, when required.

These functons will be partially controlled by pre-set commands and partly by automation techniques actuated by continuous instrument readings of such variables as chamber partial pressures and specimen temperature. The pre-set commands will be actuated by clock signals using stored commands.

For the processes which have been discussed, initial heating to melting may be accomplished at a predetermined power input. Usually the heating time will not be particularly critical, within reasonable limits. Where temperature dwells prior to melting are called for, the command memory will store the desired pyrometer reading corresponding to this dwell and will reduce the heating power to that value just required to furnish heat losses from the specimen. Maintenance of a constant temperature during the dwell will require servo regulation of the oven or heater. At the end of such a dwell, a pre-set value of heating power can be reintroduced to heat the specimen to melting. During the early phase of melting, the specimen temperature will be self-regulating and it may be desirable not to reduce the power in order to shorten the total process time. However, the pyrometer output must be continuously monitored in comparison to a threshold voltage corresponding to a pyrometer reading slightly above melting to give a rapid indication when melting is completed and superheating initiated. For some processes the heating power will be essentially removed at this time and the coil power reduced to a low value just sufficient to provide position control with relatively negligible specimen power dissipation. The latter will have very little effect upon sample cooling and solidification rates. In some cases, a dwell in the molten state may be required. Here a voltage threshold corresponding to the predetermined desired pyrometer signal output will be continuously compared to that output and servo control used to regulate the heater power. The error signal for this servo control will be simply the difference between the pyrometer output signal and the predetermined threshold signal.

Sample solidification may be recognized by the passage of a predetermined time interval. It will usually be desirable to allow the sample to cool to some predetermined temperature before recovery. The drop in pyrometer output signal to this new comparison threshold will be used to automatically initiate the recovery sequence. For vacuum environment processes, the recovery process may consist simply of actuation of the specimen grappling and storage mechanism. Where inert gases or a quenching operation are involved, other operations such as removal of quench gas from the chamber prior to specimen recovery may be required.

Automation of the specimen temperature control thus consists of a number of series steps. Within each successive time interval the heating control may be regulated differently, in some cases by passage of a fixed time interval as determined by clock signals, in other cases by comparison with a threshold appropriate to that time interval which is stored in an electronic memory. In some cases, "either-or" logic may be used such that the passage of an upper limit time interval will take over control if the expected temperature changes have not occurred by that time.

Temperature regulating and servo control devices have been available for a number of years from such suppliers as Minneapolis Honeywell Manufacturing Company. Some of these controllers allow the introduction not only of desired constant temperature dwells but linear temperature ramps where one can select a given rate of temperature rise within the capability of the heating source. Although the electronic modules for these controllers are probably available for the Spacelab and Sortie hardware with little if any change, provision of an electronic memory, logic and command unit will be required which integrates any such modules into a total temperature profile command and control unit with sufficient flexibility to handle a large range of process types, but which can also be easily reprogrammed to vary, for example, temperatures and durations of temperature dwells. The various sub-cases described for each of the four material processes investigated here were selected to show typical ranges of flexibility which should be provided.

Specimen injection and recovery will be initiated by logic and command signals which take account of elapsed time and, in some cases, chamber partial pressures or temperatures. At the beginning of this study some thought was devoted to the use of electromagnetic forces for translating the solidified specimen out of the coil system into a storage container. Previous measurements and computations in this laboratory have shown that reasonably well defined velocities can be imparted to a levitated mass by introducing a pulse of current into a specially provided coil winding. This mode of translation of specimens appears very attractive for later pilot plant facilities where it will be necessary to translate sequential samples relatively large distances due to limited storage space available in the immediate vicinity of the heating and processing facility. For the earliest experiments, however, it appears that specimens need be moved only relatively short distances in a manner which can be easily provided by an electromechanical device. Since, in any event, physical contact with the specimen before deployment and after recovery is required, and since processing of serial samples will require a reasonable amount of complexity in these deployment and storage mechanisms, it was jointly decided in a GE-Bendix working session at Ann Arbor on July 18, 1974 that it would be most sensible to integrate the specimen translation devices as an electromechanical component of the deployment and storage system, at least for Pallet payload concepts. Another important factor in this decision was the recognition that heating power and waste heat rejection are perhaps the most important constraints on pallet experiment payloads, which calls for maximizing specimen heating efficiencies. For those processes in which heating is effected by induction from the electromagnetic coil system, the presence of auxiliary coil windings for the purpose of electromagnetic translation of specimens into or out of the coil facility will, in general, represent a compromise in heating efficiency. This is because of surface currents which will be induced in the windings of these coils in the presence of the intense electromagnetic fields generated by the heating/positioning coils. For later payload processing facilities where electromagnetic specimen translation may be desirable because of the need to move specimens through large distances, electromagnetic coils to provide positioning forces in desired directions may be brought temporarily into proximity with main coil windings by mounting such auxiliary coils on a movable rod. Such a complication does not seem warranted in the initial conceptual development of Pallet containerless processing configurations.

Experience acquired in this and other laboratories relative to monitoring the vacuum or low pressure gas environments surrounding the containerless processed specimen indicates that there will be a need for considerable specialized automation of mass spectrometer and total pressure instrumentation for the pallet experiments. Although certain functions of the mass spectrometer are now routinely automated in commercially available equipment, e.g., a scan through the desired molecular weight range, in an automated space processing payload, it will be necessary to initiate such scans automatically so as to obtain required environmental gas data at appropriate times. The range of mass scanning also should be programmable in a manner appropriate to the particular material being processed and perhaps have sufficient flexibility to change its mode of scanning depending upon provisional results obtained. For example, the mass range scanned might be set to full width capability for the instrument; at less frequent intervals narrower scans through particular species masses of prime interest from the standpoint of observing vacuum outgassing of particular species or monitoring the partial pressure of a gas purposely introduced as a reactant (e.g., oxygen to effect decarburization of tungsten). Some of these commands to the mass spectrometer and total pressure gage will be stored in advance based upon a priori knowledge of the gases anticipated. Additional commands in real time might be considered to be generated based upon experiment variables in real time. For example, the sensitivity range, which is now normally set manually on commercial equipment, will require automation so as to bring certain peaks of interest within readable range. Some of the latter type of automation equipment is probably already available in the more advanced type of commercial instrumentation.

Electromechanically or hydraulically actuated valves will be required in pumping ports either to a diffusion pump or to the space environment. Other automatic valves of the needle type will be required to control admission of gases used either as an inert atmosphere or to participate in degassing reactions. The latter type of valve would be actuated either by the chamber total pressure sensor or by one of the specific mass peaks detected by a mass spectrometer.

Specimen quenching, when required, also will require automation, but probably of a very simple kind where commands are initiated by a pyrometer signal indicating that the sample has cooled to a desired value and where quenching gas is admitted only after an auxiliary signal is received indicating e.g. closure of a port to a diffusion pump or electron beam gun which requires protection from the quenching gas.

The above examples are illustrative of the various types of automation control that appears necessary and desirable for initial Sortie pallet payloads and, it is hoped, indicate the main types of automation equipment which will be required. At this stage it is probably appropriate to attempt no more than the simplest block diagrams of the equipments and functions required, such as the need for clock signal inputs, a command storage module and various command and information flow connecting each separate type of equipment.

SECTION 4

GENERAL EQUIPMENT REQUIREMENTS AND PAYLOAD GROUPINGS

4.1 INTRODUCTION

The functional requirements placed upon the design of the containerless processing facility are determined by the material to be processed and by the desired results. These requirements were discussed in detail in Reference 1 for a number of materials and processes in terms of the local environment which must be provided for the specimen in terms of intensity and frequency of applied electromagnetic fields, energy and intensity of an electron beam heater, if used, and environmental gas or vacuum. These specified environments were translated into total required vehicle power as a function of specimen melting temperature and size by making rather rough assumptions concerning achievable efficiencies of electrical equipment. It is the purpose of this report to continue this work to define in more detail the efficiencies, sizes and weights of these equipments insofar as they will determine required overall payload configurations with respect to important vehicle and mission interfaces. It will also define in somewhat more detail the types of equipment required, in particular where further development effort is required, over and above presently commercially available equipments. In order to make this work sufficiently specific to discuss these equipments in detail, it was found necessary, because of the limited scope of this study, to select several specific materials process examples. It is thus very important that these examples be so chosen as to essentially bracket the most severe requirements in terms of the main parameters of the equipment such as the highest temperatures and required heating powers, the lowest and highest efficiencies for induction heating, the total range of field frequencies required, the extremes of gas environments from high vacuum to a full atmosphere pressure and to include also an example requiring electron beam heating to achieve reasonable efficiencies.

The containerless processing facility must, above all, be capable of heating and positioning material specimens. These general requirements are discussed below.

4.2 ELECTROMAGNETIC HEATING AND MELTING

Radio frequency or eddy current heating is applicable to many materials process experiments and has been widely used in terrestrial levitation experiments with metals in which a radio frequency electromagnetic field is used simultaneously for both levitation and melting. These techniques may be extended to containerless processing experiments in space in which much larger quantities and a wider range of classes of materials can be handled. Since only very small forces need be provided, the positioning and heating functions can be, to a large extent, separated. The heating of the specimen is proportional to the square of the magnetic field intensity, H^2, and the translational force is roughly proportional to the gradient of H^2. Thus there is considerable latitude in the relative adjustment of these parameters by suitable coil design even at a fixed frequency. Since the frequency dependence of specimen heating and specimen translational forces are generally different, considerable flexibility is also available in adjusting the frequency to vary heating efficiency while at the same time achieving adequate positioning forces.

4.2.1 POWER ABSORPTION

The total power absorbed by a specimen of radius a and electrical resistivity ρ is

$$N = 3\pi a \rho_e H^2 F_1(x), \qquad \text{(MKS)}$$

$F_1(x)$ is a function of x, the latter being the ratio of sphere radius to electromagnetic skin depth in the specimen. This function, and its variation with frequency, was discussed in detail in Reference 1. In that reference it is pointed out that the values of $F_1(x)$ drop precipitiously for x values less than the order of unity so that the desire for high heating efficiencies requires that the facility frequency be so adjusted as to achieve values of x on the order of unity or greater. For specimens of radius on the order of 1 cm, such as those discussed in the specific process examples selected, this implies that the skin depth be smaller than 1 cm.

4.2.2 RANGE OF ELECTROMAGNETIC SKIN DEPTHS FOR MATERIALS OF INTEREST

Figure 4-1 shows the variation of electromagnetic skin depth δ as a function of frequency for various resistivities. Because of the wide range considered, the straight lines have been chosen to correspond to constant resistivities, each differing from the next by two orders of magnitude (factors 10^2). Also indicated by the arrows and labels are ranges of typical specimen resistivities. In the examples chosen for detailed study in this work, we have chosen two extremes of material resistivities which require radio frequencies spanning the entire range considered for electromagnetic processing. The examples of beryllium and tungsten have cold resistivities near the lower limit for metals and alloys of interest and require frequencies only on the order of 10 kHz to achieve skin depths less than 1 cm. Preheated zirconia, on the other hand, requires frequencies on the order of 15 mHz in order to achieve a corresponding skin depth and x of unity or greater. Figure 4-1 shows the specific operating regions of interest for three processing examples discussed in detail in this report.

The fourth material process example which was chosen in Section 1, namely alumina glass, has a resistivity even when preheated which exceeds values for which electromagnetic containerless processing is feasible and hence is a candidate for acoustic or other means of positioning. Equipment details related to this processing example will not be discussed in this report but may be obtained from other contractors currently studying these alternative techniques. Materials having electrical resistivities intermediate to the extremes represented by beryllium and preheated zirconia will, in general, call for frequencies intermediate to the two extremes already mentioned. As was discussed in Reference 1 and should be mentioned here, the choice of frequency is allowed rather wide latitudes provided that an x of unity or greater is achieved. This is because of the fact that power required for positioning is generally rather low which allows a non-optimum choice of frequency, within limits, and furthermore the induction

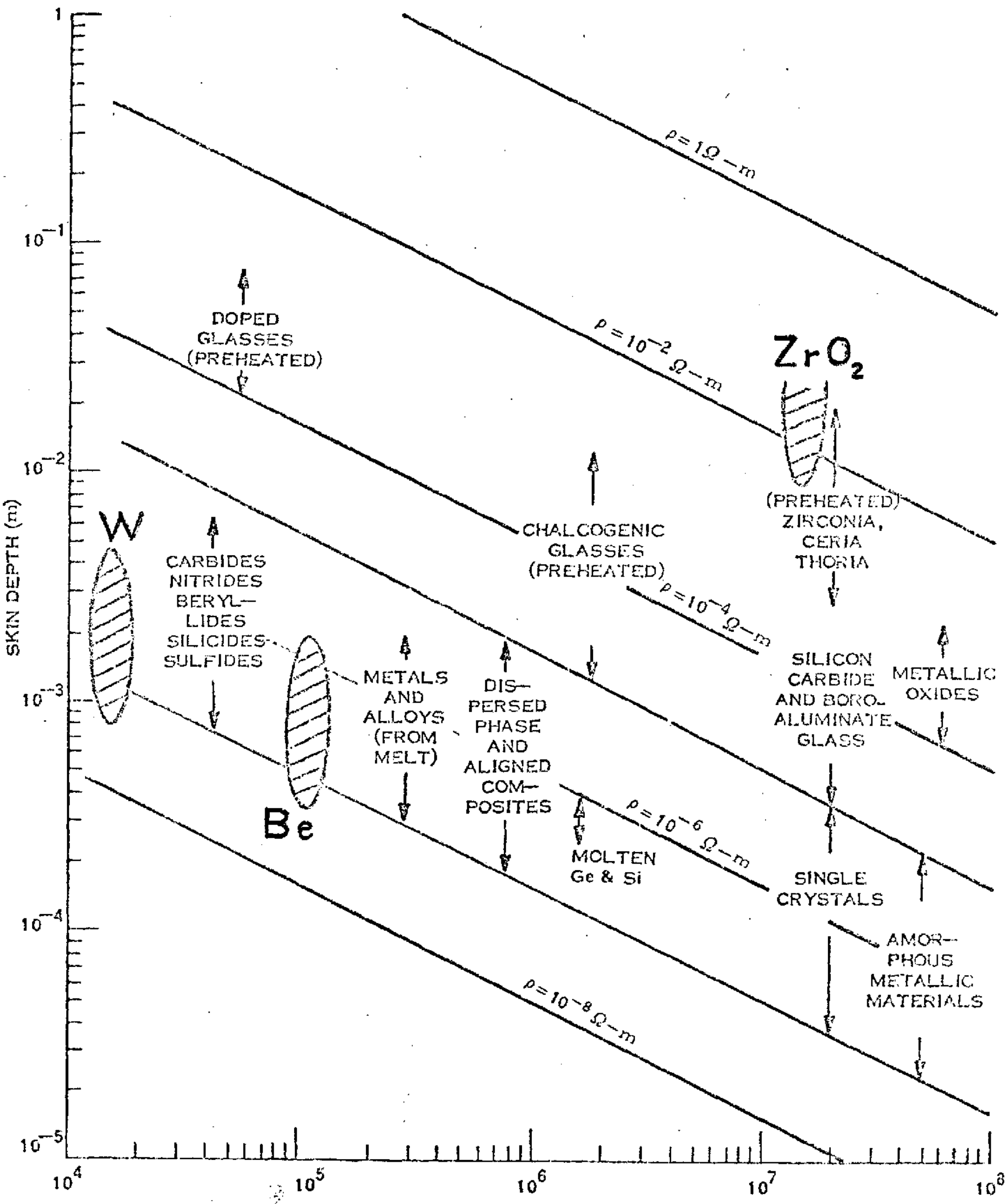


Figure 4-1. Electromagnetic Skin Depth Versus Frequency and Resistivity With Regions of Interest for Specific Examples

heating efficiency increases to an asymptotic value as the frequency is raised above the value which is optimum for positioning forces. These matters will be discussed later.

4.2.3 EFFICIENCY OF INDUCTION HEATING

The power dissipated by the heating/positioning coil current in the coil may be calculated from the customary I^2R formula with the resistance of the coil, R, calculated at the operating frequency using the corresponding skin depth in copper. If this power be called P and the power dissipated in the specimen be called N, as in Section 4.2.1, then the efficiency of heating the specimen in that coil may be calculated from N/(N+P). Graphs illustrating this heating efficiency are given in Reference 1 and one additional example is given here in Figure 4-2 for a zirconia sphere, 2.5 cm in diameter. It was assumed in the preparation of this graph that the resistivity of the material is 1 ohm-cm, which implies a temperature in the range 2000°C to 2400°C.

4.3 R.F. FREQUENCY REQUIREMENTS AND EXPERIMENT GROUPING RATIONALE

The two most important material parameters which determine the required electrical frequencies and powers are the melting temperature and electrical resistivity. The melting temperature determines the total heating power which must be delivered to a given size specimen. The resistivity for a given size specimen determines the frequency which must be used to achieve reasonably efficient positioning and heating. These matters are discussed in detail in Reference 1. For the present purposes it may be more useful to display the relationship between melting temperature, resistivity and optimum frequency in the form of Figure 4-3. In this presentation, a total available d.c. bus power of 5 kw is assumed. It is considered that the specimen size is the maximum which allows melting, given this total fixed power. These maximum sizes were illustrated in the final section of Reference 1 and will not be repeated here. The reason for the non-monotonic behavior of these curves is the arbitrariness

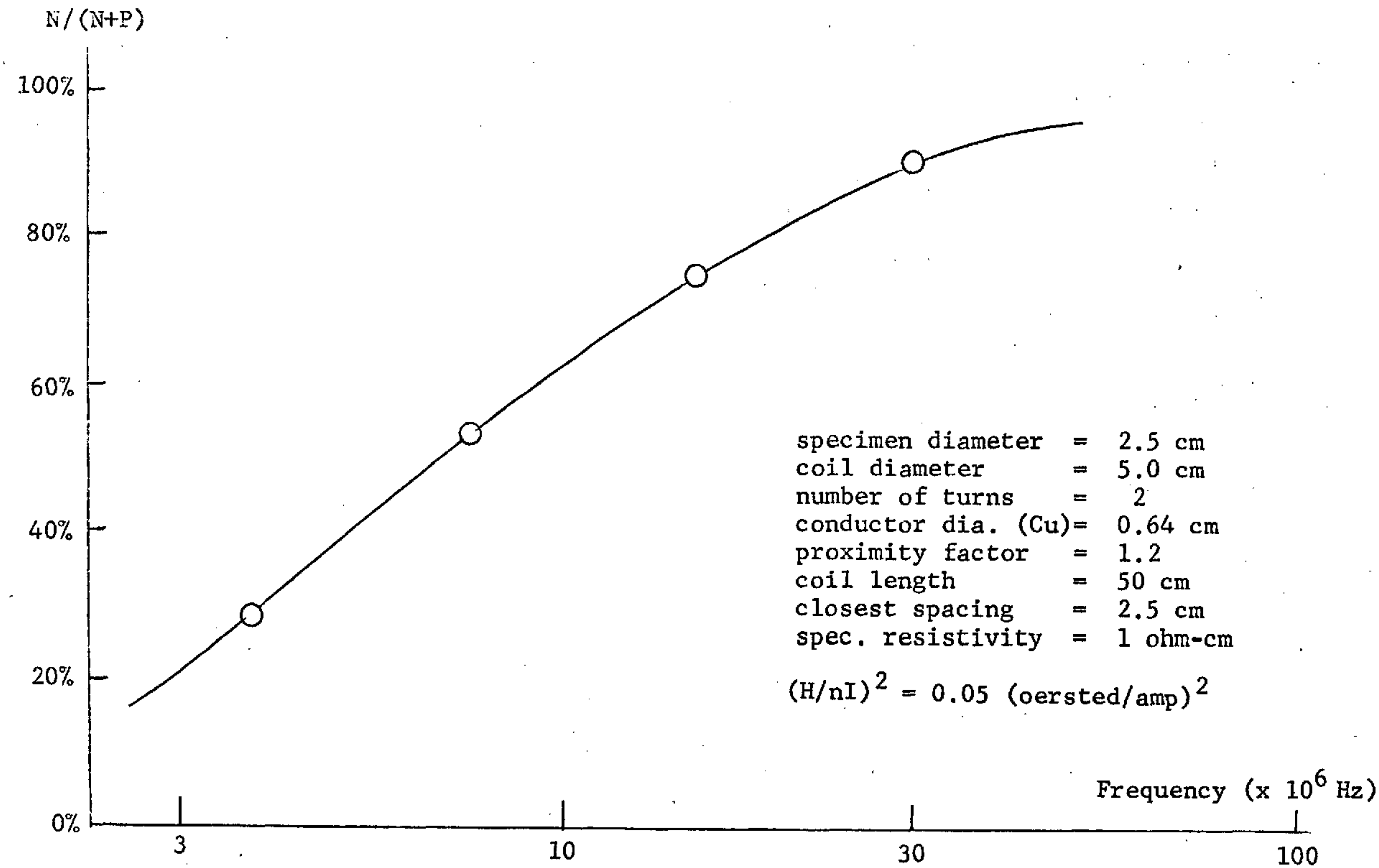


Figure 4-2. Efficiency of Heating a ZrO_2 Specimen at 2000° in a Baseball Coil

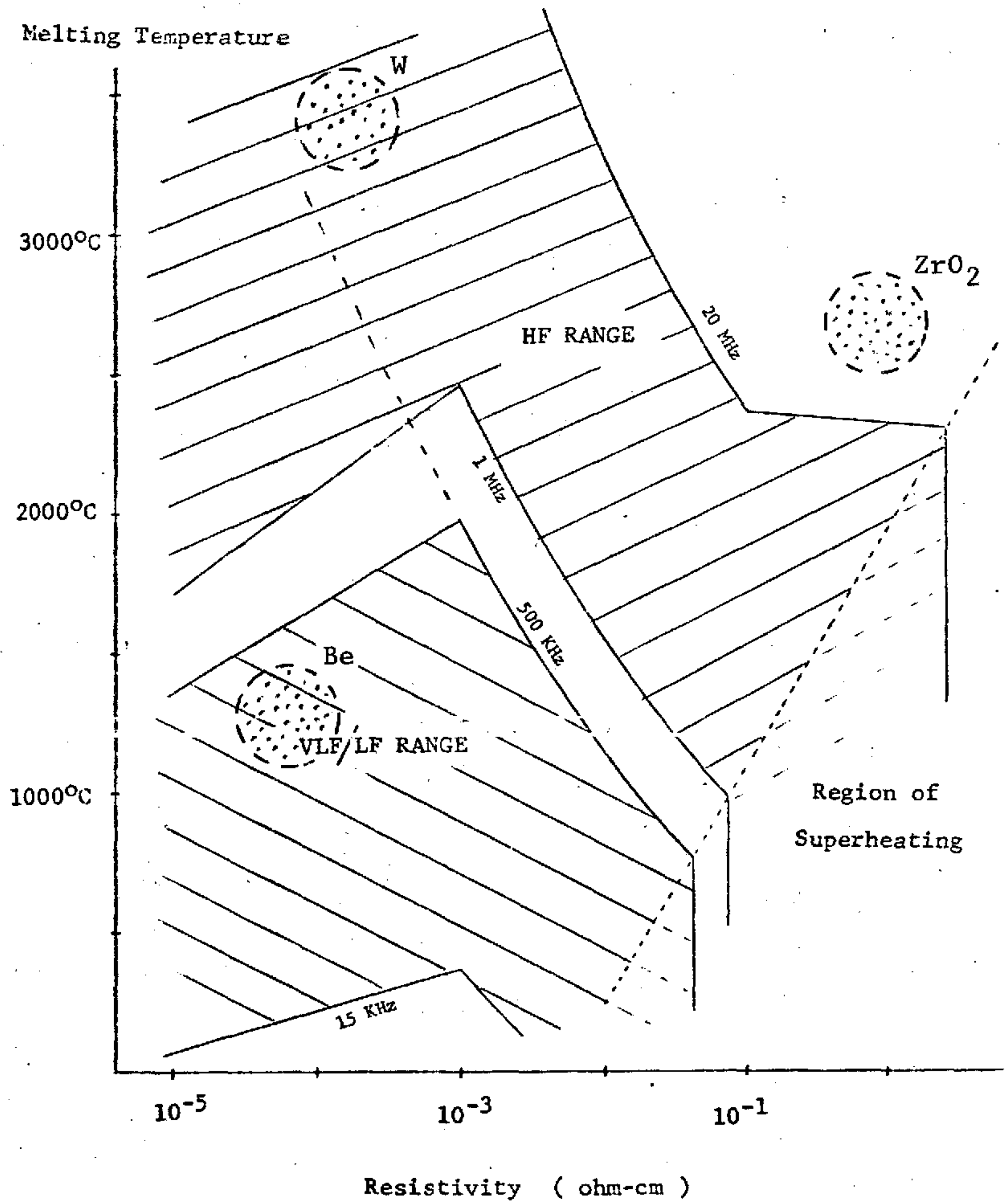


Figure 4-3. Regions of Applicability of HF and VLF/LF Equipment
(For 5 Kw DC bus power and specimen thermal emissivity 0.8.)

allowed in choice of frequencies for good conductors where positioning forces are so high that a wide latitude is available in choice of frequency. This latitude was utilized to restrict the frequencies considered to a minimum of 10 kHz and a maximum of 20 mHz. Each material process candidate can be considered to define a small circular region of the plane of Figure 4-3. The horizontal width to these regions represents the variation in resistivity as the material is heated and melted. Considering the five decade range of abscissa, even a one decade resistivity variation is to be considered "small" in this context. We can see immediately that a broad division of all specimen candidates can be made according to whether the frequency requirement to achieve positioning and melting lies in the HF regime or the VLF/LF range. Each of these types of equipment can be made to cover well over one decade in frequency, but it is generally inappropriate to use the same kinds of components and construction to cover both ranges. The boundary between the LF and HF regimes is rather arbitrary and here has been chosen to be broadly representative of ranges customarily serviced by commercial or amateur HF gear on the one hand and the maritime, beacon and naval radio services on the other hand. Assuming that pallet payloads would probably incorporate only one or the other general types of r. f. equipment, this diagram already suggests one rationale for grouping of candidate experiments into specific shuttle payloads. Plotted as dotted regions on the figure are the beryllium and zirconia process examples which in this report are described in detail at sizes corresponding to the maximum which can be melted with 20 kw of available power. The corresponding specimen diameters will be approximately twice the meltable diameter for the 5 kw bus power assumed in Figure 4-3. These larger sizes allow use of frequencies approximately on the order of four times lower than those illustrated in the figure, since at constant x the frequency varies as the inverse square of specimen radius, as discussed in Reference 1. Thus we see that the division between the payload groupings in terms of LF or HF equipment depends to some extent upon the total available power.

Also shown as a dotted region on Figure 4-3 is the resistivity-melting temperature regime for tungsten. The maximum size specimen which can be melted by electromagnetic induction assuming even a maximum facility power of 20 kw is too small to be of real interest as already discussed in Reference 1. For this reason more efficient electron beam heating is recommended for this candidate process. The tungsten example chosen may thus be considered representative of other refractory metals which would call for electron beam heating, where this is possible.

4.4 ELECTRON BOMBARDMENT HEATING AND MELTING

Materials for which the total secondary electron emission coefficient can exceed unity are materials which can be electron beam heated and melted in the levitated condition, without the need for grounding of the heated specimen. The electrostatic potential of the levitated material will automatically adjust itself to that value, in the range of a few tens of volts positive, which causes an adjustment of the net number of low energy secondaries emitted such that the total electron flux leaving the specimen equals the total flux of electrons in the impinging beam.

For many materials, thermionic electron emission will become adequate to maintain a zero net electron flux prior to achievement of melting temperatures. Initial grounding of the cold specimen can then be effected by mounting the unmelted specimen on a grounded, possibly retractable, "sting" of the same material to reduce contamination.

4.4.1 MATERIAL CLASSES FOR ELECTRON BEAM HEATING AND MELTING

A general discussion of total secondary emission was given in Reference 1. We here summarize briefly by way of example a list of materials according to whether they can or cannot be considered as candidates for electron beam heating and then discuss broadly the rationale to be used in deciding which heating method is to be used for those materials capable of being heated alternately by an electron beam or by induction heating.

4.4.1.1 Prime Candidates

Those materials which are the best candidates for electron beam heating and melting while in the levitated state are:

1. The metals Iridium, Osmium, Platinum, Rhenium, Palladium, Silver, Gold, Rhodium, Tungsten, Tantalum, Molybdenum, Bismuth, Cadmium, Lead and Tin.

2. Alloys of these metals and alloys of these metals with other metals in which these metals predominate.

3. The metal oxides such as ZrO_2, ThO_2, and CeO_2 having high electron emission coefficients. However, it is likely that these materials will be processed in a low partial pressure of oxygen which would mitigate against use of the electron beam. The high resistivity of these materials, when preheated, allows highly efficient r.f. heating in any event so that the motivation for use of the electron beam would be absent.

4.4.1.2 Secondary Candidates

Materials which can be heated by low energy electrons starting from the cold condition in the containerless state are:

1. The metals Copper, Nickel, Iron, Hafnium, Cobalt and Niobium.

2. Alloys of these metals and alloys of these metals with prime candidate metals.

3. Compound Semiconductors such as an Indium-Antimonide, Sb_2Ce_3, Lead Sulfide, Sb_2S_3, $BiCs_3$, Bi_2Cs, and GeCs.

4. Semiconducting glasses such as the chalcogenide glasses.

5. Amorphous metallic glasses such as PdSi.

For those materials such as Ni, Fe, Hf, Co and Nb, thermionic electron emission as the materials become incandescent would allow neutralization of any charges imparted by the incident electron beam so that for these and other high melting materials, the electron beam energy can be any convenient value. Similar remarks apply to most carbides, nitrides and borides.

4.4.1.3 Unlikely Candidates

Finally, there are those materials not considered to be candidates for electron beam melting while levitated.

1. The alkalai metals and other low melting metals for which thermionic emission is insufficient to effect grounding prior to reaching temperatures at which the specimen must be deployed in a containerless state.
2. The elemental semiconductors, Germanium and Silicon.
3. Some compound semiconductors such as Gallium Arsenide, GeS and others.

4.4.2 EXPERIMENT GROUPINGS IN TERMS OF HEATING METHOD USED

For those materials in the last of the three groups discussed above and similar materials for which electron beam heating cannot be utilized for freely floating specimens due to insufficient secondary electron emission, electromagnetic induction heating is the obvious choice for the earliest experiments in the Space Laboratory and Shuttle programs. For those materials which can be heated alternatively by electron beam bombardment, some freedom of choice as to heating method is available. Implicit in this discussion is the assumption that heating and melting by direct solar radiation at the focus of a deployable collecting mirror, although very attractive where large heating powers are required, must be deferred for later evolutionary phases of these programs where the mission constraints imposed by the use of such mirrors can be justified for pilot plant studies. For those materials for which electron beam heating and melting is possible, the choice between this as against induction heating will depend to a large extent upon the specimen melting power required. Where this taxes the total power capabilities of the facility, the improved efficiency of electron beam heating will be a decided advantage for materials in the metal and alloy categories. For materials of relatively high resistivity, the efficiency of induction heating will be nearly equal tothat for electron beam heating and either method of heating is a logical candidate. For some experiments the smaller temperature gradients achievable by induction heating where the heat source is distributed over a large fraction of the outer specimen surface is to be preferred. A secondary factor favoring the electron beam heat source is the greater freedom in choice of radio frequency coil configuration which need not now be so tightly coupled to the specimen. Later applications in which electromagnetic translation of the specimen are to be considered would thus be eased since the reduction in induction heating efficiency due to the presence of auxiliary coils provided for translation would be acceptable. Our three examples discussed in detail in the following illustrates each of the three situations just described. The extreme melting power requirements for tungsten, for which induction heating is considerably less efficient than electron beam heating, make the latter a clear choice. The zirconia example illustrates the case where the induction heating efficiency is similar to the electron beam heating efficiency and the former is chosen to eliminate the requirement for a separate heat source. The beryllium is an example of the third category for which electron beam melting of an isolated specimen is not possible at conventional electron beam energies so that induction heating is chosen. The melting power requirements are sufficiently modest as compared to tungsten that reasonable specimen sizes can be considered.

4.5 ENVIRONMENTAL GAS REQUIREMENTS

The residual gases present in vacuum systems are generally H_2O, O_2, N_2, CO, CO_2, H_2 and CH_4. These gases originate from system leaks, outgassing of the hot furnace surfaces, the pumping system, and the metal being heated. The pressure of each of these gases is dependent upon the furnace history and the test conditions. During the heating-outgassing cycle, the total pressure of these gases will increase to a maximum value and then decrease to a value characteristic of the pumping system. In order to perform certain processes, then, such as decarburization, the partial pressures of residual gases, such as O_2 in this case, must be adjusted to favor the degassing reactions.

Careful consideration must be given to the use of an inert gas during degassing. A major disadvantage of the use of an inert gas is the resulting difficulty of controlling the concentrations of the active impurity gases. With permissible partial pressures for inert gas during degassing at the level of 10^{-4} torr or less and the allowable concentrations of impurity gases in an inert gas at one atmosphere pressure ranging from fractional parts per million to 10^{-5} parts per million or less the allowable impurity concentrations in the inert gas may be so low as to prevent precise measurement.

It is most likely that the production of many glasses such as zirconia, alumina, silica, etc., will require an ambient pressure ranging from a low vacuum (above 10^{-3} torr) to one atmosphere pressure. An oxygen atmosphere might be used to prepare many glasses. As an example, BeO tends to form polymeric vapor species as $(BeO)_n$, where n = 2, 3, 4, 5, 6. Even a small partial pressure of O_2 will suppress this incongruent vaporization. It should be noted that the use of such vacua does not permit the use of an electron beam for heating.

Of the examples chosen for specific study, both general types of environmental gas requirements are illustrated. The tungsten example is illustrative of experiments requiring relatively good vacua, the beryllium requiring either a vacuum or a low pressure gas environment and the zirconia requiring a partial atmospheric pressure of oxygen.

4.6 POSITIONING FORCE REQUIREMENTS

Calculations and experience with earth orbiting satellites of long lifetime indicate that accelerations due to atmospheric drag, slow facility rotations and differences in location from the geodesic point in the satellite are on the order of 10^{-4}g or less under normal circumstances assuming that high rotational velocities of the vehicle will be avoided during operation of the Containerless Processing Facility. The largest accelerations of the facility may due to astronaut body motions, if pumping of vehicle fluids or operation of thrusters is inhibited during material processing. As discussed in Reference 1, it is considered sufficient for a Containerless Processing Facility to be prepared to accelerate specimens at a rate of 10^{-3}g maximum in the vicinity of the center of the positioning coil.

4.6.1 POSITION CONTROL FORCES

The alternating magnetic field produced by the coil current in a Containerless Processing Facility induces eddy currents in the specimen being positioned. Between these induced currents and the coil currents are forces, which, if the alternating magnetic field is nonuniform, will result in a net translational force. As developed in Reference 1, the force may be written as:

$$F = \frac{-10^7}{4} a^3 \, G(x) \, \mathrm{grad}\, B^2 \qquad \text{(MKS units)}$$

where a is the specimen radius, B is the value of the applied flux density in webers m^{-2} before introduction of the specimen and G(x) is a function of the quantity x, the ratio of spherical specimen radius a to electromagnetic skin depth within the specimen. The skin depth is a function of the electrical resistivity of the specimen and the frequency of the applied electromagnetic field as discussed above in Section 4.2.2. It may be noted that for small values of x, $G(x) = 0.0254\,x^4$ and for large x, G(x) approaches unity. This expression for force was used in determining the positioning power requirements in Section 5.0 of this report by calculating the required force from the mass multiplied by the acceleration it must experience, here 10^{-3}g, and then solving for the required grad B^2. The quantity $\mathrm{grad}(B/I)^2$ is determined by the geometry of the positioning coil and specimen. In this manner, one may find a value of I, the coil current, which is needed to produce the required value of grad B^2. The sustaining of this current in a coil of effective AC resistance R results in a power dissipation I^2R in the coil and in a dissipation N in the specimen, as discussed above (Section 4.2.1).

SECTION 5

SPECIFIC EQUIPMENT REQUIREMENTS

5.1 INTRODUCTION

General characteristics of any containerless processing system were discussed in Section 4. In this section are described specific examples of such systems recommended for use on a remotely operated, "pallet" experiment, as might be carried on a space shuttle. The materials processed in these examples are:

Tungsten
Beryllium
Zirconia

In each experiment the material is heated to a temperature somewhat below its melting point to permit outgassing to take place, after which it is melted, heated to a temperature somewhat above its melting temperature and then allowed to cool and solidify. The specimens range in diameter from 2.6 to 4.0 cm, but in any one experiment, only one material is to be processed and all specimens of that material are to be of one size. In each case a cusp coil such as that shown in Figure 5-1 is assumed.

5.2 TUNGSTEN EXPERIMENT

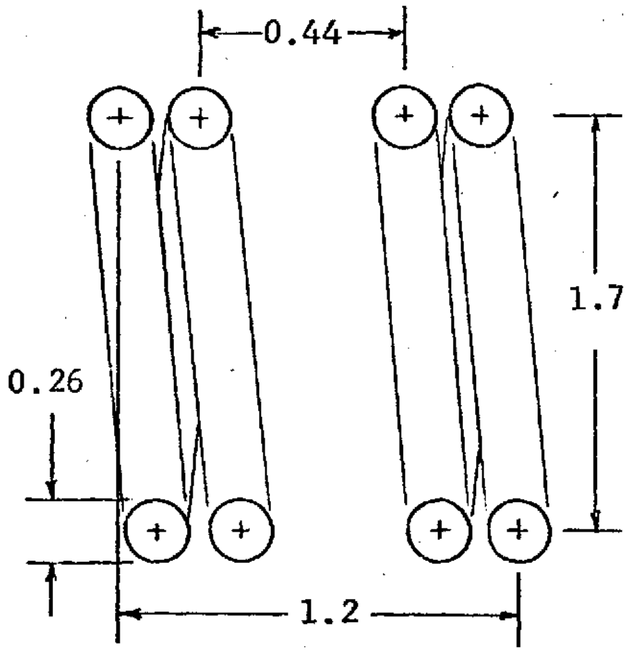
An electron beam is used to melt the specimens, each 2.6 cm in diameter, and a cusp coil is used to position the specimen electromagnetically.

5.2.1 HARDWARE

A block diagram showing the major components which comprise the experiment is given in Figure 5-2. The functions of those items directly related to heating and positioning are described in 5.2.1.1, and the functions of all others are described in 5.2.1.2.

5.2.1.1 Heating and Positioning Components

(1) Heating via an electron beam--



(Multiply numbers in figure by specimen diameter to obtain actual dimensions)

Figure 5-1. Cusp Coil

The electron beam high voltage supply draws its power directly from a vehicle d. c. source for maximum efficiency of power conversion and supplies up to 13 kw at voltages of the order of 15, 000 volts to the electron beam gun. Because of this high voltage present in the gun and the consequent danger of arcing, the high voltage supply should be equipped, as is standard with electron beam power supplies, with an arc suppression circuit which momentarily reduces the voltage to a low value when an arc occurs. This high voltage supply should also be capable of being turned off automatically for some short, predetermined time, if the pressure in the vacuum chamber rises to values too high for safe operation of the electron gun.

The electron beam gun directs an intense beam of electrons at the tungsten specimen which is heated through the absorption of the kinetic energy of

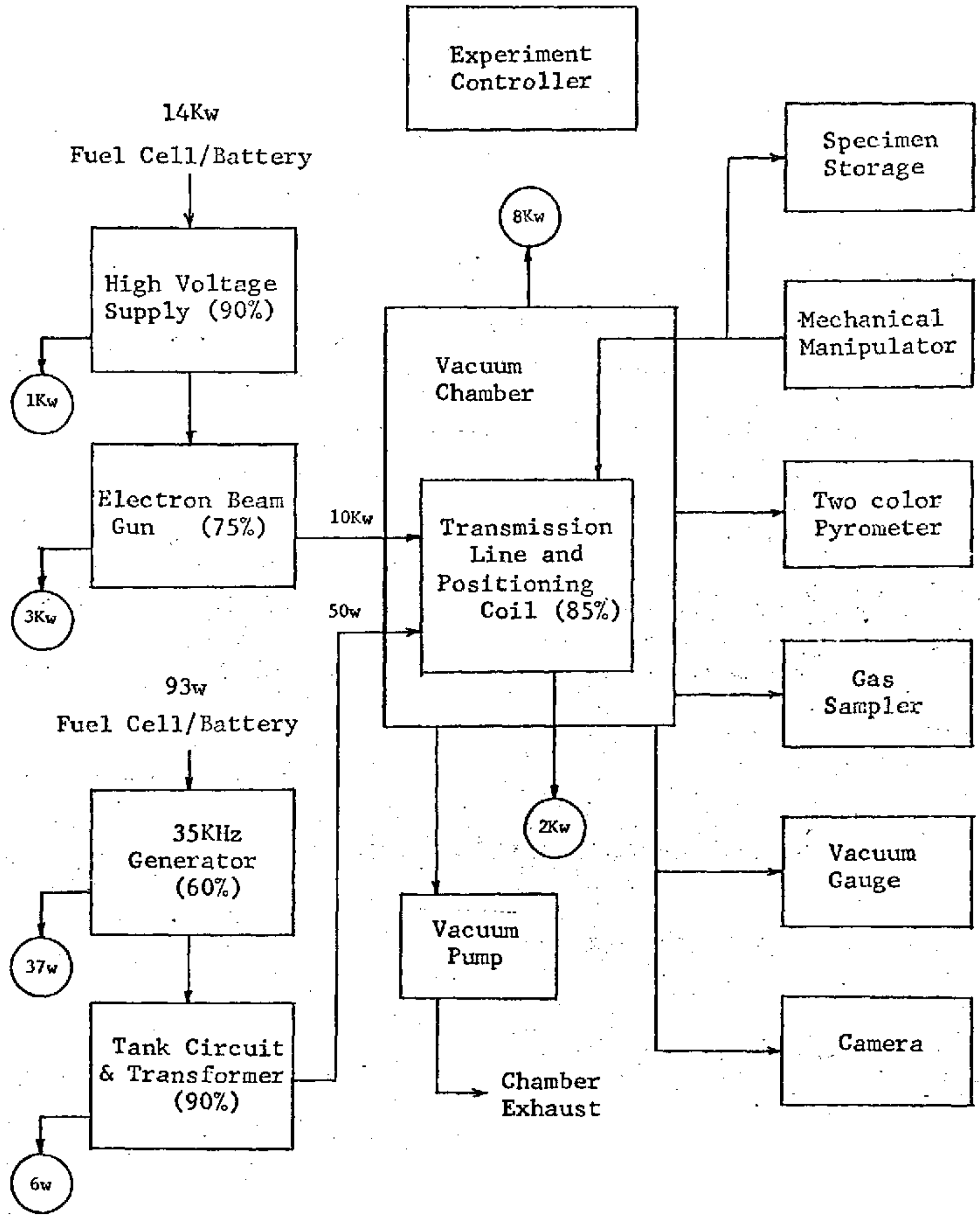


Figure 5-2. Block Diagram of Tungsten Experiment with Thermal Dissipation at Maximum Power Given in Circles

the electrons. In the event that the specimen is not located properly in the positioning coil, there should be a device behind the coil which the beam will strike, causing the beam to be turned off and the experiment recycled.

(2) Positioning via r.f. induction

The electromagnetic positioning system draws its power directly from a vehicle d.c. source for maximum electrical efficiency. The r.f. generator supplies up to 50 watts of power at approximately 35 kHz. This generator should be capable of supplying power at this level during release and recapture of the specimen by the mechanical manipulator, and at approximately one one-hundredth of this level during the melting, heating and solidification of the specimen. The lower power level is designed to supply 10^{-4}g acceleration to the specimen with less than 0.5 cm displacement of the specimen from the center of the coil.

The tank circuit and transformer provide the high current required by the positioning coil and the transmission line conveys this current to the coil.

The frequency of the r.f. positioning current was chosen as 35 kHz to maximize the ratio of force/power.

5.2.1.2 Ancillary Components and Data Acquisition

During the time the experiment is in operation, those components listed below which produce data to be recorded to assist in the analysis of the experiment's results should have their outputs recorded at a rate of 1 sec^{-1} and the time at acquisition of each bit of data should be known to the nearest hundredth of a second.

(1) Camera -

Photographic coverage is required of each processing cycle beginning at the latest at the time of release of each specimen by the manipulator in the coil and ending no sooner than at the specimen's removal from the coil. Preferably two views of each specimen should be photographed and each should be done via mirrors to minimize obscuration of the camera's view of the specimens by deposition of tungsten on optical surfaces. Neutral density filters will have to be placed in front of the camera's lens as the specimens become hot to prevent overexposure of the tungsten image.

(2) Vacuum Gauge

Pressure in the vacuum chamber should be recorded during each heating and cooling cycle. Anticipated pressure range is 10^{-8} to 10^{-3} torr and the required accuracy is $\pm 10\%$ of the reading.

(3) Gas Sampler

Many commercial mass spectrometers are available which could be considered for this application. These, typically, are too bulky for the space application and would require extensive repackaging. For example, the Veeco Model No. GA4R Mass Spectrometer presently being used in ground based tungsten outgassing and undercooling studies fills a six foot high standard relay rack. Another candidate source for this type of instrument, rather than repackaging commercially available equipment, would be the mass spectrometers developed for space science applications such as analysis of upper atmosphere species. It is unlikely, however, that any of these already space qualified instruments will have the required range and flexibility as a general purpose instrument for the Space Laboratory or Shuttle pallet containerless processing payloads.

(4) Pyrometer

The range of temperatures probably cannot be met by one instrument unless it has automatic ranging capability. The temperature of the tungsten will rise to above 3420°C and it is desirable to resolve ±10°C with an accuracy of about ±10°C. Emissivity changes are expected but because of the accuracy requirement it may not be possible to calibrate this out using earth bound tests so a two color scheme is appropriate. Space-qualified two color pyrometers capable of this performance are not readily available and probably represent a development effort.

(5) Manipulator

In the tungsten experiment described here, there is no need for the use of electromagnetic impulse devices to move specimens from one location to another. The tungsten specimens solidify so quickly upon cessation of heating that mechanical manipulators which are prepared to grasp relatively hot specimens without damaging the surfaces of the specimens are preferred. The fingers of this manipulator and all other materials which come in close proximity of the positioning coil and transmission line must contain little, if any, electrically conducting material. The presence of such material could disturb the operation of the positioning coil by causing energy to be absorbed from the r.f. electromagnetic field and, if assembled in such a way as to permit large conducting loops, the material would cause the r.f. field to be distorted. The manipulator must work in conjunction with the specimen storage container to preserve the identification of each specimen as well as protecting each from contamination. The manipulator must contact each specimen with clean surfaces.

(6) Specimen Storage

The storage container must protect each specimen from the shock and vibration involved in spacecraft operations as well as contamination which might occur either from direct contact of one specimen with another or from the gaseous products produced by one specimen coming in contact with another specimen.

5.2.2 SEQUENCE OF OPERATIONS

(1) Chamber evacuated

(2) All instrumentation turned on

(3) Initiate processing cycle

(4) Manipulator places specimen in coil

(5) Positioning coil energizes to hold specimen at its center

(6) Manipulator removed

(7) Electron beam heating begins as shown in time line, Figure 5.3

(8) Electron beam turned off at end of heating cycle

(9) After specimen is cool enough to handle, mechanical arm removes it from positioning coil and places it in storage container

(10) Next specimen placed in coil as in (4), above, and heating cycle is initiated.

(11) Above sequence is continued until six specimens have been processed

(12) All instrumentation turned off

(13) Vacuum pump turned off.

5.2.3 POWER REQUIREMENTS AND THERMAL DISSIPATION

The power required to heat the specimen to the temperatures shown in Figure 5.3 was calculated using the principles given in Section 4 and, using the estimated power conversion efficiencies given in parentheses in the component blocks in Figure 5-2, the total power required from the vehicle was calculated.

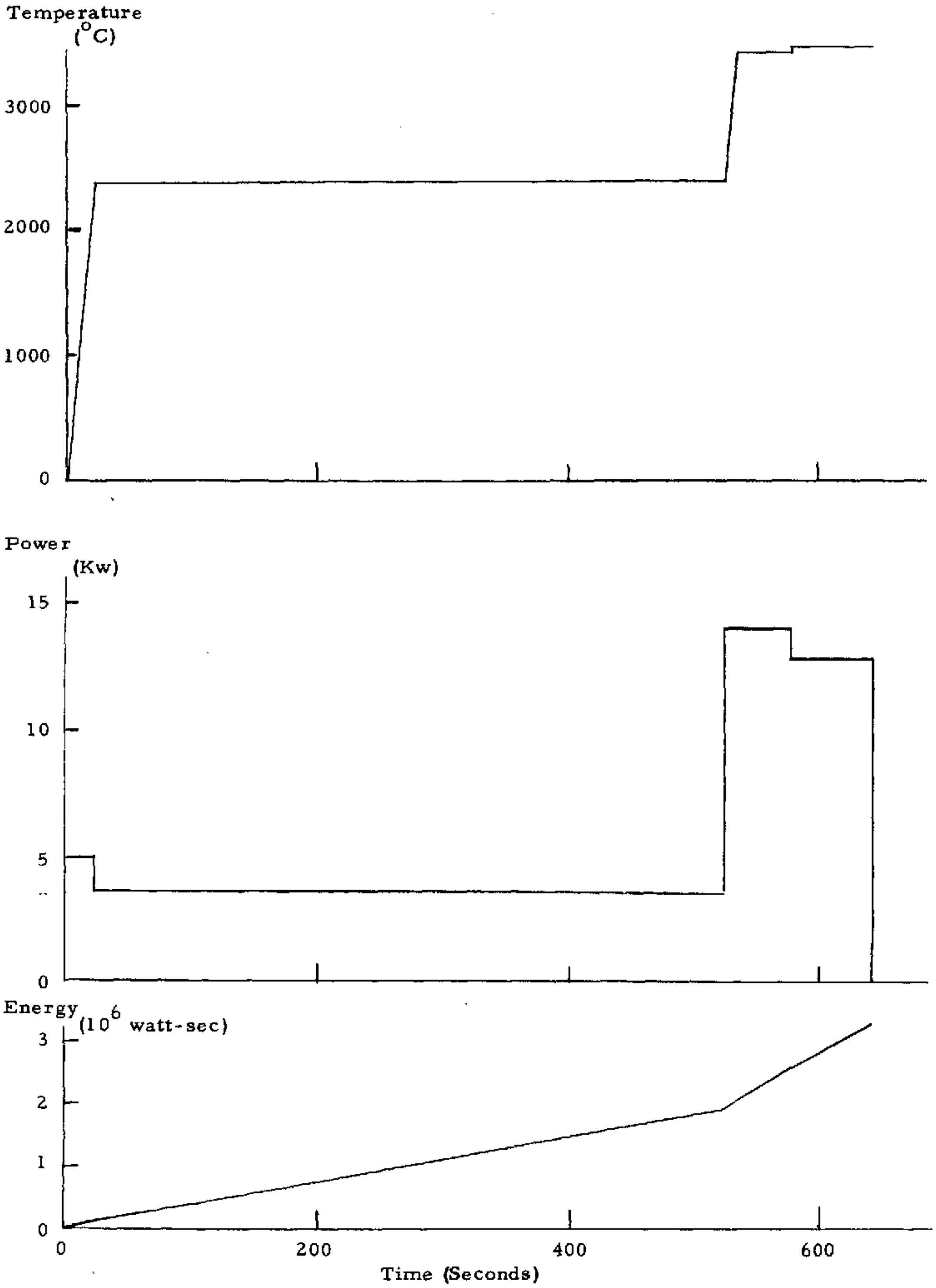


Figure 5-3. Temperature, Power and Energy Time Lines for a Tungsten Specimen 2.6 cm in Diameter

It is this total power which is plotted in the middle of Figure 5-3 and the total energy required through the use of this power is plotted at the bottom of that figure.

The heat to be removed from each heating and positioning component was calculated and shown, for maximum power consumption, in circles in Figure 5-2. Thermal dissipation at lower total power levels may be obtained in proportion to the total power consumed. In calculating dissipation in the vacuum chamber, it has been assumed that 80% of the energy radiated by the specimen ultimately strikes and remains in chamber walls. The power representing this energy is shown in Figure 5-2 in the circle above the box representing the chamber. The remainder of the energy radiated by the specimen was assumed to enter the positioning coil to be removed by a cooling fluid circulating through the coil and transmission line, along with the energy dissipated in the coil and transmission line by the coil current. This latter power, the summation of power from three sources at maximum power consumption, is shown in Figure 5-2 in the circle below the box representing the chamber.

5.2.4 RF EQUIPMENT

(1) Coil

The coil for the tungsten specimen will fit a 5.2 cm spherical surface inscribed through the average conductor centerlines. This coil will require 50 watts for positioning and contributes negligible heating so it does not seriously influence the cooling time. Because of the relatively small power required, this coil could be made somewhat larger at more power if this is desirable for materials of larger sizes.

The coil will be placed within the vacuum chamber and will therefore have a line through a penetration leading outside the chamber to an impedance matching transformer and reactance compensation (tuning) network. This line will dissipate about 6 watts if short and of moderate cross section.

Cooling of the feed line is optional but the coil will require the removal of several hundred watts being radiated to it by the very hot tungsten.

(2) Reactance Compensation

At the modest power of 50 watts the capacitive VAR will be about 10^3 and at 300 V rms, the capacitor is about 0.025 μF. Because this obviously will not match the coil directly, the capacitor will have its own impedance matching transformer winding.

(3) Loading

As the tungsten is heated from +25°C to 3500°C, the resistivity varies from about 5 micro-ohm-cm to 150 micro-ohm-cm. This represents a change in absorbed power of 5.5 to 1, or roughly from 5 or 6% to 30%. This amounts to about a 25% increase in loading of the amplifier and can be handled in two ways: It can be corrected by a switched tap or two on the impedance matching transformer, or the amplifier can just be permitted to lose efficiency at one end or the other of the range. The preferred way is to match the amplifier with the cold tungsten and allow a 25% mis-match for the hot tungsten.

(4) R.F. Oscillator/Amplifier

This unit will be transistorized and operate at 120 watt minimum input with an overall efficiency of at least 60% properly matched. It must be capable of survival with repeated short circuits in the coil assembly as well as with severe reactive load variation. This last requirement is easily met by a simple oscillator and power amplifier.

5.3 BERYLLIUM EXPERIMENT

Electromagnetic induction is used to heat and position the specimens, each 4.0 cm in diameter, in a cusp coil.

5.3.1 HARDWARE

A block diagram showing the major components which comprise the experiment is given in Figure 5-4. The function of those items directly related to heating and positioning are described in 5.3.1.1 and the functions of all others are described in 5.3.1.2.

5.3.1.1 Heating and Positioning Components

(1) Heating via induction

A 100 kHz generator draws its power directly from a vehicle d.c. source for maximum efficiency of power conversion. However, its efficiency is estimated at only 60% due to the continually changing electrical conductivity of the specimen as it is heated, which is reflected back to the tank circuit as a change in effective impedance. This results in the 100 kHz generator feeding power to a circuit not optimumly matched to it.

The large current which is caused to flow in the heating/positioning coil generates an intense r.f. field in the vicinity of the specimen and the resulting current induced in the specimen causes it to be heated. The power levels shown in Figure 5-4 are the amounts of power involved during this heating and melting phase of the experiment. The frequency of 100 kHz was chosen to obtain a high efficiency of heating.

(2) Positioning via induction

The power required for heating produces forces which are far in excess of forces needed for positioning. Thus, while the specimen is maintained at an elevated temperature, the specimen is tightly held at the center of

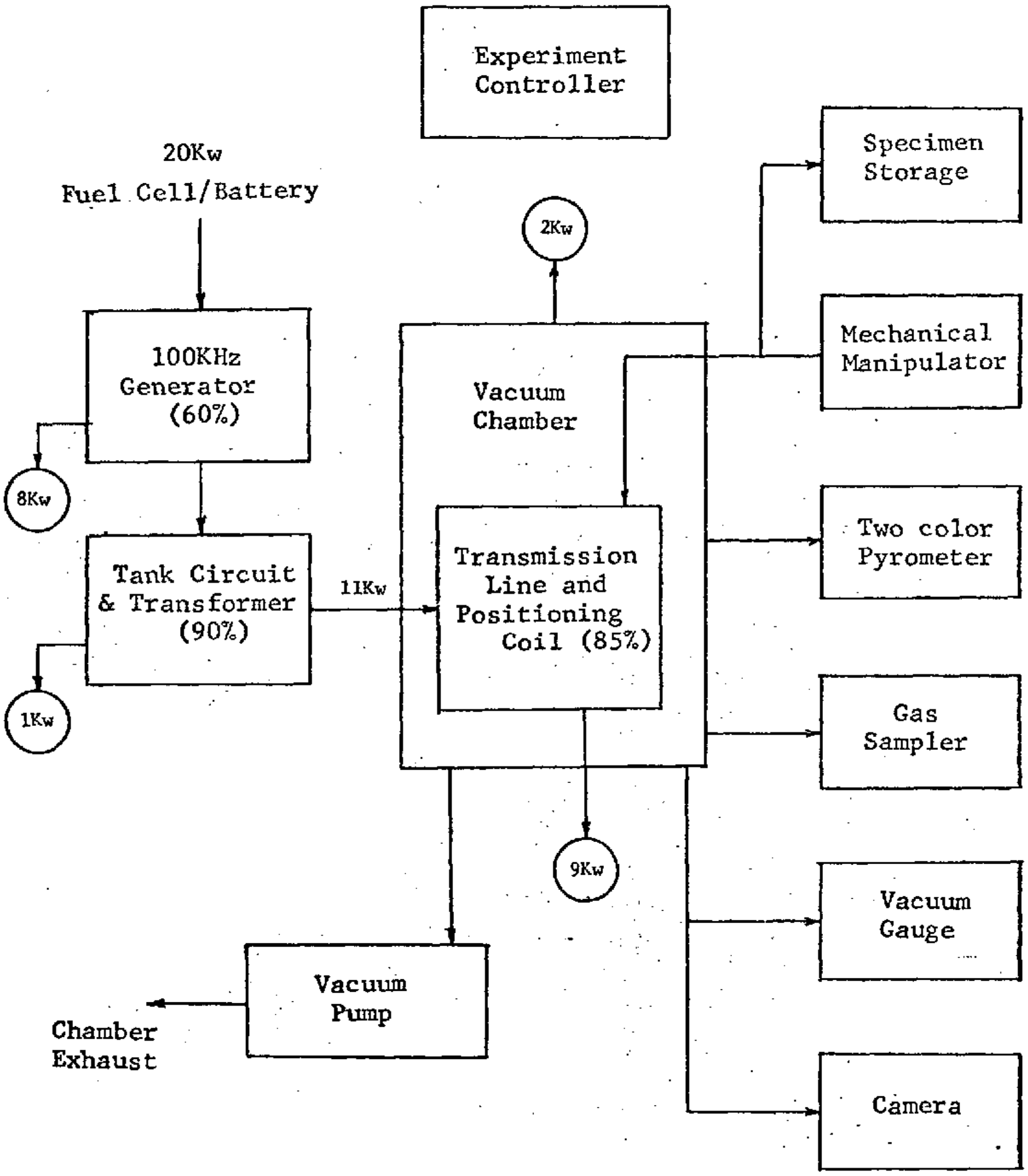


Figure 5-4. Block Diagram of Beryllium Experiment with Thermal Dissipation at Maximum Power Given in Circles

the coil. However, during the periods that the specimen is either being placed in the coil, being removed from the coil or being allowed to cool, the current in the coil must be reduced to that value which is just sufficient to maintain the specimen's position within the coil, without significantly heating it. The amount of power which would be drawn from the vehicle d.c. supply during placement in and removal from the coil and during cooling is only several hundred watts instead of the 20 kw shown in Figures 5-4 and 5-5.

5.3.1.2 Ancillary Components and Data Acquisition

During the time the experiment is in operation, those components listed below which produce data to be recorded to assist in the analysis of the experiment's results should have their outputs recorded at a rate of 1 sec^{-1} and the time at acquisition of each bit of data should be known to the nearest hundredth of a second.

(1) Camera

Photographic coverage is required of each processing cycle beginning at the latest at the time of release of each specimen by the manipulator in the coil and ending no sooner than at the specimen's removal from the coil. Preferably two views of each specimen should be photographed and each should be done via mirrors to minimize obscuration of the camera's view of the specimens by deposition of beryllium on optical surfaces. Neutral density filters may have to be placed in front of the camera's lens as the specimens become hot to prevent overexposure of the beryllium image.

(2) Vacuum Gauge

Pressure in the vacuum chamber should be recorded during each heating and cooling cycle. Anticipated pressure range is 10^{-8} to 10^{-3} torr and the required accuracy is $\pm 10\%$ of the reading.

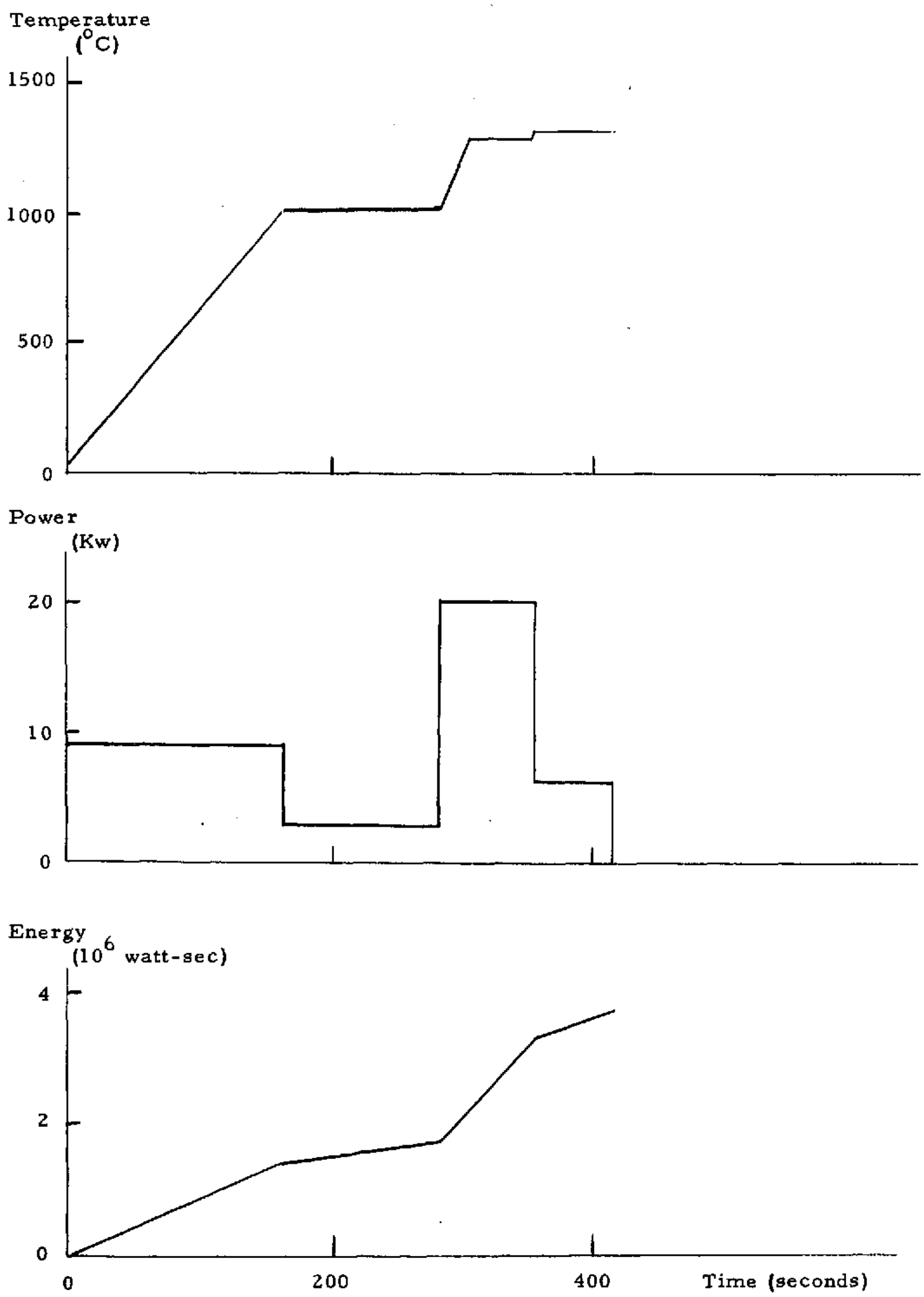


Figure 5-5. Temperature, Power and Energy Time Lines for a Beryllium Specimen 4.0 cm in Diameter

(3) Gas Sampler

Two types of experiments with containerless melts of beryllium have been suggested by Kawecki Berylco. In the first type, pure beryllium would be melted and then allowed to resolidify after substantial undercooling. These attempts to obtain a finer grain beryllium crystal structure will depend upon the achieving of substantial undercoolings which in turn may require some vacuum purification of the melt prior to initiation of cooling. For this type of experiment, a mass spectrometer of the type discussed previously under the tungsten example would be appropriate.

Another approach to attempting to improve service properties of beryllium involves melting and resolidification of beryllium containing a small amount of beryllia dispersion. In this case, a partial pressure of inert gas may be appropriate. For some early experiments of this type, the mass spectrometer may be dispensed with for simplicity if the purity of the specimen has been accurately controlled previously and reliance placed upon the pressure gauge to measure partial pressure of the environmental gas.

(4) Pyrometer

Two color pyrometry should be employed to obtain and record the color temperature of each specimen during each heating and cooling cycle. A range up to about 1500°C should be provided and accuracy of data should be $\pm 1\%$ of absolute temperature reading.

(5) Manipulator

In the beryllium experiment described here, there is no need for the use of electromagnetic impulse devices to move specimens from one location to another. The specimens solidify sufficiently quickly upon cessation of heating that mechanical manipulators which are prepared to grasp relatively hot specimens without damaging the surfaces of the specimens are preferred. The fingers of this manipulator and all other materials which come in close proximity of the positioning coil and transmission line must contain little, if any, electrically conducting material. The presence of such material could disturb the field of the positioning coil by causing energy to be absorbed from the r.f. electromagnetic field and, if assembled in such a way as to permit large conducting loops, the material would cause the r.f. field to be distorted. The manipulator must work in conjunction with the specimen storage container to preserve the identification of each specimen as well as protecting each from contamination. The manipulator must contact each specimen with clean surfaces.

Because of the toxicity of beryllium oxide, special precautions will have to be observed in the design of the equipment to allow removal of the specimens and cleaning of the chamber and other equipment which may be contaminated prior to reuse. It is expected that this requirement will call for special attention in vacuum chamber, manipulator and specimen storage container design to render them more accessible to simple post-flight disassembly and cleaning operations.

(6) Specimen Storage

The storage container must protect each specimen from the shock and vibration involved in spacecraft operations as well as contamination which might occur either from direct contact of one specimen with another or from the gaseous products produced by one specimen coming in contact with another specimen.

5.3.2 SEQUENCE OF OPERATIONS

(1) Chamber evacuated

(2) All instrumentation turned on

(3) Initiate processing cycle

(4) Manipulator places specimen in coil

(5) Heating/positioning coil energized to hold specimen at its center

(6) Manipulator removed

(7) Induction heating begins as shown on time line, Figure 5-5

(8) Power to coil reduced to permit cooling

(9) After specimen is cool enough to handle, power to coil is increased to increase positioning forces.

(10) Mechanical arm recaptures specimen and places it in storage container

(11) Next specimen is placed in coil as in (4) above, and heating cycle is initiated

(12) Above sequence is continued until six specimens have been processed

(13) All instrumentation turned off

(14) Vacuum pump turned off (if used)

5.3.3 POWER REQUIREMENTS AND THERMAL DISSIPATION

The power required to heat the specimen to the temperatures shown in Figure 5-5 was calculated using the principles given in Section 4 and using the estimated power conversion efficiencies given in parentheses in the component blocks in Figure 5-4. The total power required from the vehicle was calculated. It is this total power which is plotted in the middle of Figure 5-5 and the total energy required through the use of this power is plotted at the bottom of that figure.

The heat to be removed from each heating/positioning component was calculated and shown, for maximum power consumption, in circles in Figure 5-4. Thermal dissipation at lower total power levels may be obtained in proportion to the total power consumed as would be the case, for example, for the two lower rates of energy consumption given in Section 5.3.1.1 for positioning without significant heating. In the case of the positioning coil, the transmission line leading to it and the vacuum chamber, it has been assumed that 80% of the energy radiated by the specimen ultimately strikes and remains in the chamber walls. The power representing this energy is shown in Figure 5-4 in the circle above the box representing the chamber. The remainder of the energy radiated by the specimen was assumed to enter the heating/positioning coil to be removed, by a cooling fluid circulating through the coil and transmission line, along with the energy dissipated in the coil and transmission line by the coil current. This latter power, the summation of power from three sources at maximum power consumption, is shown in Figure 5-4 in the circle below the box representing the chamber.

5.3.4 R.F. EQUIPMENT

(1) Coil

The processing coil for beryllium will be the nominal 8 cm diameter design (twice the specimen diameter). This process might better be performed in a smaller coil of about 7 cm nominal diameter due to the poor power coupling to the high conductivity beryllium.

This coil provides the heating and large positioning forces during heating. During the melting and dwell the coil must dissipate about 9 kw for a total r.f. input power of 10 kw. If the coil were made smaller as mentioned above, the coupling efficiency would improve and less power would be required. It is estimated that reducing the coil to 7 cm nominal diameter would reduce power requirements by at least 20%.

This coil has to communicate with the r.f. power generator through a chamber penetration and transmission line. The line will dissipate about 1.5 kw. The r.f. generator must be matched to the coil as well as to the tuning capacitor for optimum loading and for this purpose an impedance matching transformer is required.

(2) VAR Compensation (Tuning)

A major piece of hardware at 10 kw and 100 kHz is the reactive volt-ampere compensation capacitor. This unit must have a peak V.A.R. capacity of about $0.2 \times 10^{+6}$ volt-amperes at 100 kHz. Industrially these capacitors are air cooled or water cooled depending upon the thermal design. It will dissipate about 500 watts.

(3) Loading

The resistivity of beryllium varies from 4-6 $\mu\Omega$-cm to 150 $\mu\Omega$-cm with temperature and hence its loading will change (increase) about 15% as the specimen heats. Because efficiency of the power generator is very important it is advisable not to deliver full power to the cold specimen. As mentioned earlier, until the specimen heats to its higher temperature there is no appreciable radiation heat loss. As the specimen reaches its highest temperatures (about 1280°C) the driving power should be increased. At the high temperatures, full power and good load matching for high efficiency should be achieved simultaneously thus eliminating the need for impedance matching taps or variometer-type devices.

(4) R.F. Generator

This unit will operate at 100 kHz and will be transistorized. It will consist of multiple power stages (about 10) of about 2 kw input each. They will be designed such that the failure of one will not affect the operation other than a 10% reduction in output. In fact, if the design is conservative, the remaining nine could deliver the full power assuming the generator temperature is monitored or kept low. About

8 kw must be removed from this generator for 12 kw output, for the maximum input power of 20 kw. The power time line (Figure 5-5) shows a lower input power of 9 kw for the initial temperature ramp. Assuming a constant 0.6 efficiency, the coil power will be about 5 kw.

5.4 ZIRCONIA EXPERIMENT

After preheating to 2000°C, electromagnetic induction is used to heat and position the specimens, each 2.6 cm in diameter, in a cusp coil.

5.4.1 HARDWARE

A block diagram showing the major components which comprise the experiment is given in Figure 5-6. The functions of those items directly related to heating and positioning are described in 5.4.1.1 and the functions of all the others are described in 5.4.1.2.

5.4.1.1 Heating and Positioning Components

(1) Preheating

When zirconia is at room temperature, its resistivity is too high in relation to the ability to dissipate power within it, even at extremely high frequencies, to permit either inductive heating directly, without a susceptor, or inductive positioning. For this reason, the zirconia specimen must be heated to approximately 2000°C by other means such as in a resistively heated or inductively heated oven. The initial rise in temperature to 2000°C shown in Figure 5-7 is accomplished by this pre-heat oven.

Rather than providing a separate heater to preheat the material, the simplest approach would appear to be utilizing the r.f. equipment

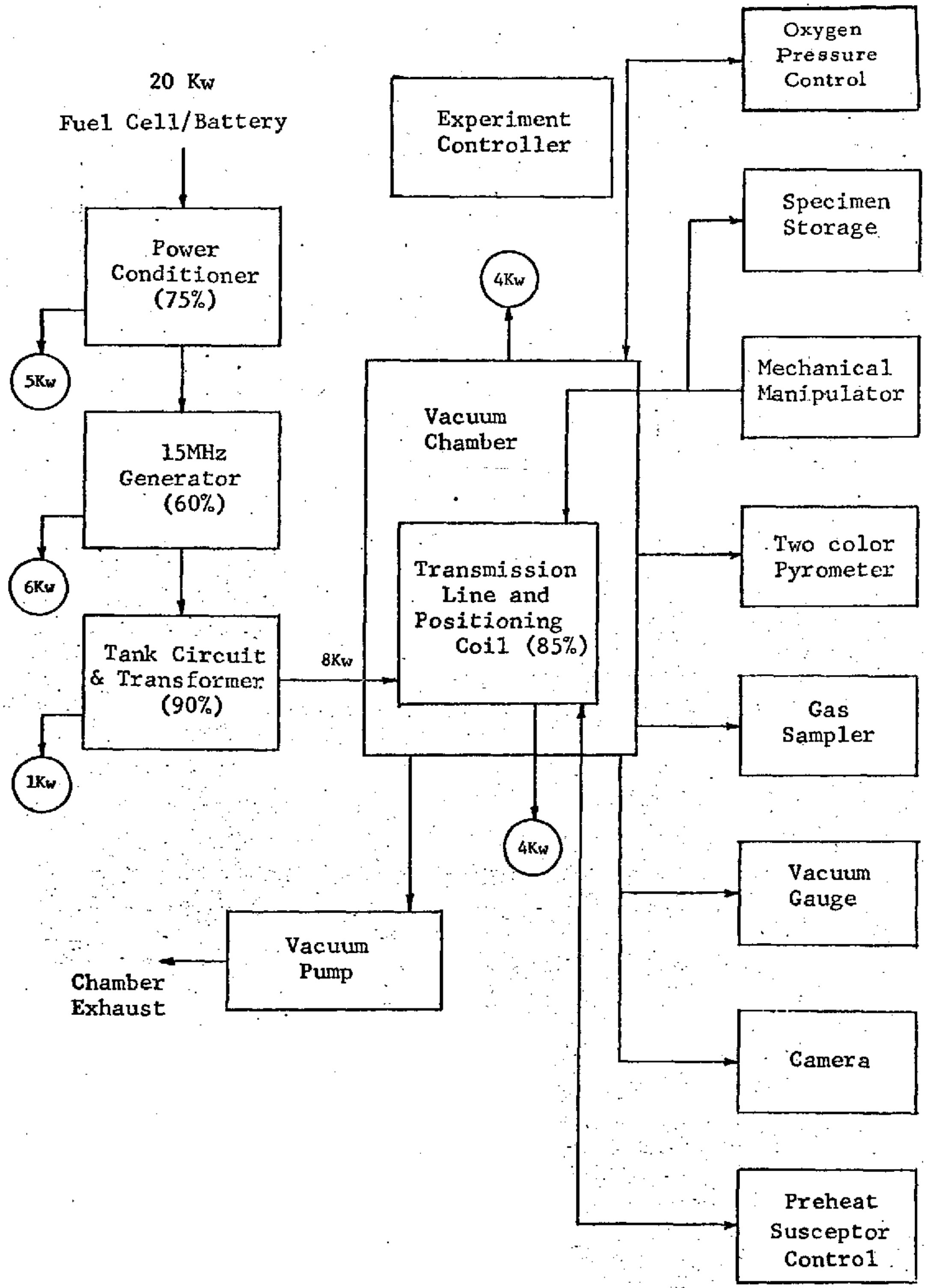


Figure 5-6. Block Diagram of Zirconia Experiment with Thermal Dissipation at Maximum Power Given in Circles

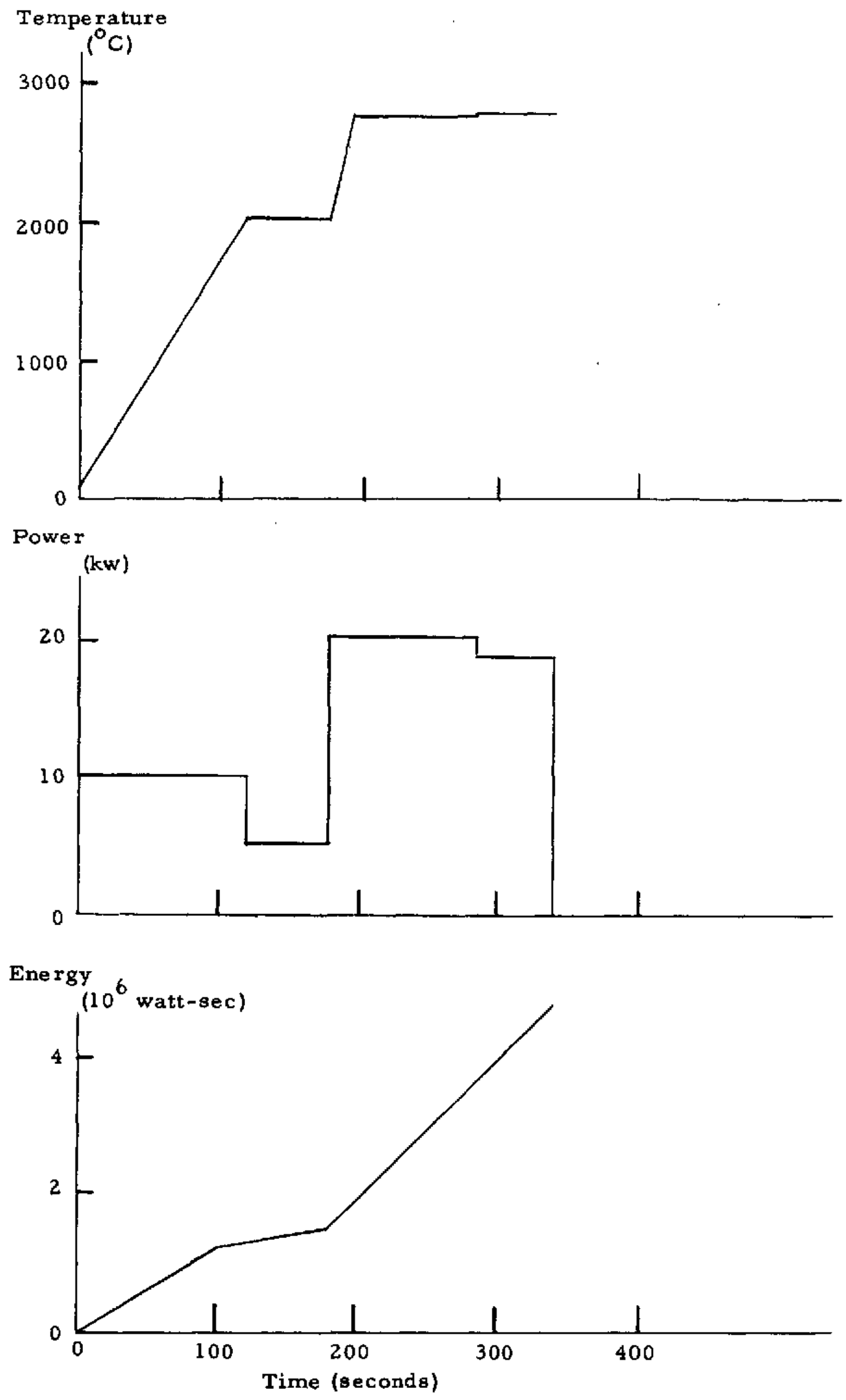


Figure 5-7. Temperature, Power and Energy Time Lines for a Zirconia Specimen 2.6 cm in Diameter

already provided and to temporarily introduce a thin walled conducting susceptor surrounding the specimen. It will probably be feasible to avoid even the introduction of a separate r.f. coil for this preheating but to introduce the susceptor containing the specimen into the main coil windings already provided for specimen positioning and melting. The susceptor wall thickness and material would be so chosen as to provide loading to the r.f. system which approximately matches that expected for the preheated zirconia after the susceptor is withdrawn. Since a rather large reduction in heating efficiency can be accepted in heating the zirconia to the relatively modest preheating temperature, this consideration of load matching need only be very approximate.

The susceptor may be used for another important purpose in that it will be able to reduce the cooling rate of the specimen to protect against shattering from too rapid cooling. To accomplish this, the r.f. is gradually reduced until the specimen temperature is 2000°C. A preheated susceptor then mechanically holds the specimen and the power is then adjusted so that the susceptor and specimen cool together at a safe rate.

(2) Heating via induction

A power conditioning unit, drawing power directly from a vehicle d.c. source provides the d.c. voltage and filament power required to operate the 15 mHz generator. The transformer and tank circuit cause a large a.c. current to flow in the heating/positioning coil. The currents induced in the specimen cause the specimen to be heated and the frequency of 15 mHz was selected to obtain a high efficiency of heating. The power levels shown in Figure 5-6 for the 15 mHz heating/melting components and vacuum chamber are the amounts involved during the heating and melting phase of the experiment after preheating. The power levels given in Figure 5-7 for the rise to 2000°C are applicable to the preheating phase of the experiment only, during which time the specimen is held in the Preheat Susceptor and power for electromagnetic positioning is not required.

(3) Positioning via induction

The power required for heating produces forces in excess of forces needed for positioning. Thus, while the zirconia specimen is maintained at temperatures in excess of approximately 2000°C by the heating/positioning coil, it is also adequately held within the coil. However, if the heating power were significantly reduced to permit rapid cooling of the specimen, the forces would be extremely small, and once the temperature falls below 2000°C it will be impossible to exert any significant force upon the specimen without generating a significant amount of heat within it. Thus, relatively moderate cooling rates to 2000°C followed by constraint and removal after subsequent cooling in the susceptor is indicated, as already mentioned.

5.4.1.2 Ancillary Components and Data Acquisition

During the time the experiment is in operation, those components listed below which produce data to be recorded to assist in the analysis of the experiment's results should have their outputs recorded at a rate of 1 sec^{-1} and the time at acquisition of each bit of data should be known to the nearest hundredth of a second.

(1) Camera

Photographic coverage is required of each processing cycle beginning at the latest at the time of release of each specimen by the manipulator in the coil and ending no sooner than at the specimen's removal from the coil. Preferably two views of each specimen should be photographed. Neutral density filters will have to be placed in front of the camera's lens as the specimens become hot to prevent overexposure of the zirconia image.

(2) Vacuum Gauge

Pressure in the process chamber should be recorded during each heating and cooling cycle. Anticipated pressure range is 1 to 1000 torr and the required accuracy is $\pm 10\%$ of the reading.

(3) Oxygen Pressure Controller

A partial pressure of oxygen is required in the vacuum chamber to prevent undesirable disintegration of the specimen. The function of the oxygen pressure controller is to maintain a partial pressure of oxygen in the range 1 torr to atmospheric. To accomplish this it must contain both a supply of oxygen and a partial-pressure-of-oxygen sensor. The output of this sensor should be recorded continually during operation of the experiment.

(4) Pyrometer

Two color pyrometry should be employed to obtain and record the color temperature of each specimen during each heating and cooling cycle. Anticipated range is up to about 2800°C and accuracy of data should be $\pm 1\%$ of absolute temperature reading.

(5) Manipulator

In the zirconia experiment described here, there is no need for the use of electromagnetic impulse devices to move specimens from one location to another. The zirconia specimens solidify so quickly upon cessation of heating that mechanical manipulators which are prepared to grasp relatively hot specimens without damaging the surfaces of the specimens are preferred. The fingers of this manipulator and all other materials which come in close proximity of the positioning coil and transmission line must contain little, if any, electrically conducting material. The presence of such material could disturb the generation of the positioning forces by causing energy to be absorbed from the r.f. electromagnetic field and, if assembled in such a way as to permit large conducting loops, the material would cause the r.f. field to be distorted. The manipulator must work in conjunction with the specimen storage container to preserve the identification of each specimen as well as protecting each from contamination. The manipulator must contact each specimen with clean surfaces.

(6) Specimen Storage

The storage container must protect each specimen from the shock and vibration involved in spacecraft operations as well as contamination which might occur either from direct contact of one specimen with another or from the gaseous products produced by one specimen coming in contact with another specimen.

5.4.2 SEQUENCE OF OPERATIONS

(1) Chamber flushed and filled to appropriate O_2 pressure

(2) All instrumentation turned on

(3) Initiate processing cycle

(4) Specimen placed in susceptor within r.f. coils

(5) Preheat r.f. power turned on

(6) After required temperature has been reached, the susceptor is withdrawn and the specimen deployed in the position control space. Full power is applied to the coil. Induction heating is assumed to begin at approximately 2000°C and continued as indicated in Figure 5-7.

(7) Power to coil turned off

(8) After specimen is cool enough to handle, manipulator removes specimen from coil and places it in storage container.

(9) Next specimen is placed in preheat oven as in (4), above, and preheating is initiated.

(10) Above sequence is continued until six specimens have been processed

(11) All instrumentation turned off

(12) Vacuum pump turned off.

5.4.3 POWER REQUIREMENTS AND THERMAL DISSIPATION

The power required to heat the specimen to the temperatures shown in Figure 5-7 was calculated using the principles given in Section 4 and using the estimated power conversion efficiencies given in parentheses in the component blocks in Figure 5-6. The total power required from the vehicle was calculated. It is this total power which is plotted in the middle of Figure 5-7 and the total energy required through the use of this power is plotted at the bottom of that figure.

The heat to be removed from each heating/positioning component was calculated and shown, for maximum power consumption, in circles in Figure 5-6. Thermal dissipation at lower total power levels may be obtained in proportion to the total power consumed. In the case of the positioning coil, the transmission line leading to it and the vacuum chamber, it has been assumed that 80% of the energy radiated by the specimen ultimately strikes and remains in the chamber walls. The power representing this energy is shown in Figure 5-6 in the circle above the box representing the chamber. The remainder of the energy radiated by the specimen was assumed to enter the heating/positioning coil to be removed, by a cooling fluid circulating through the coil and transmission line, along with the energy dissipated in the coil and transmission line by the coil current. This latter power, the summation of power from three sources at maximum power consumption, is shown in Figure 5-6 in the circle below the box representing the chamber.

5.4.4 RF EQUIPMENT

(1) Coil

The coil will probably be the nominal 5 cm facility but will consist of a single turn each side of the cusp (or a 1 turn baseball coil) of flattened copper tubing. The process may require an atmosphere of oxygen or an inert gas so breakdown may limit the coil powers that can be used, hence the use of a low inductance coil of 1 turn. Because of the relatively high heating efficiency, the coil dissipates only 4 kw for 8 kw input, the chamber dissipating the other 4 kw.

(2) Feedline

Because of the low coil impedance, the line will be heavy and short to the impedance matching transformer. It may be either parallel wide flattened tubes or a large co-ax, the parallel line being preferred. In fact the parallel line may be simply a loop from the chamber extending to the matching transformer.

(3) VAR Compensation (Tuning)

The capacitor will probably be one or two large vacuum units of about 300 pf total capacity. These units are generally air cooled in industrial applications but liquid cooling can be employed, the critical area being the feed-thru seals.

(4) Loading

The loading problem for zirconia is not as severe as for the metals. Once the material is preheated, its resistivity comes down to one ohm-cm and remains at that value up to the melting temperature of 2677°C. If the furnace is used with a susceptor for preheating the specimen, the loading for preheat will be different than the loading of the specimen alone after preheat. Because the highest power is required after preheat, the loading should be set for that condition and reduced power used for preheat.

(5) R.F. Generator

The frequency of operation of the oscillator and amplifier is 15 mHz at a delivered power of 8 kw r.f. This unit is a vacuum tube unit and will require a power conditioner. Standard broadcast fixed frequency techniques should be employed with the major departure from conventional design made for impedance matching (loading) to the heating coil facility.

SECTION 6

GENERAL EQUIPMENT DEVELOPMENT PROBLEMS

6.1 INTRODUCTION

Much of the design of the Electromagnetic Containerless Processing Facility is straightforward and utilizes techniques in r.f. induction heating, electron beam heating, vacuum technology, pyrometry, etc. which have been utilized in industrial processes for many years. Nevertheless, the integration of these various technologies into an integrated Containerless Processing Facility, particularly if it is of the automated variety, will require considerable development design effort. In this section we shall discuss several of the areas which will require the most careful attention as indicated by technology development contract work already done on space containerless processing or indicated by related industrial experience. These problems will be illustrated for the two extremes of frequency contemplated and for the power levels already mentioned which are assumed for the Shuttle pallet payloads. Probably the greatest effort is required in design of modern inverter power conditioners which can operate with high efficiency from the vehicle d.c. power source since the use of standard industrial equipment operating from 60 cycle sources is inappropriate. Furthermore, without making use of these modern techniques at the higher power levels, current indications are that heat rejection from such equipment will pose major design problems in the heat rejection system. For this reason, the weight and power estimates given for the r.f. equipment in the next section have been based upon the use of these high frequency power conditioning circuits utilizing solid state devices. Since the detailed nature of these circuits required consideration in order to arrive at weight, volume and efficiency figures, the subsequent section will also discuss in considerable detail the design techniques required in the power conditioning and low frequency power amplifiers. Technology for the h.f. generators is considered rather mature; hence, no particular development problems in that area are expected other than the transformer and loading circuit to allow use of the unconventional low load impedance presented by the work coil.

6.2 SPECIMEN DEPLOYMENT INTO COIL FACILITY

6.2.1 PREHEATED SPECIMEN

The insertion implement may seriously affect the electromagnetic field within the coil if made of conducting materials, consequently care in its design is required. As an example, 10^{-1} ohm-meter material resistivity of sizes over a few millimeters will seriously affect the field at 15 mHz and will absorb power from the coil to a marked degree. Conversely, a good electrical conductor of small size will affect the field only slightly and will not absorb near as much power.

With a preheated specimen, it is desirable to switch off the preheating mode rapidly, remove the implement or susceptor, then switch on the melting mode power. The use of active damping in this case will go a long way toward easing the restraint on residual specimen motion on release and thereby facilitate the rapid insertion required.

6.2.2 COLD SPECIMEN

There is no need for rapid insertion of the specimen when cold because there is no need for temperature regulation. The residual motion of the specimen will require relatively rapid removal of the implement. If the implement can be designed not to have a serious effect on the field, the r.f. can be turned on while it is being withdrawn thereby allowing more time for the insertion process. Parts of the insertion implement that come no closer to the work coil than one coil diameter will not seriously affect the field within the work coil but will absorb power; therefore, these parts should be good electrical conductors or insulators. Parts that must pass through the work coil must be poor conductors with low dielectric loss if the coil is to be energized with these parts within the coil structure.

6.2.3 SPECIMEN CAPTURE AND POST PROCESS STORAGE

This subject is being studied under another contract (NAS8-30741) and will not be discussed here.

6.2.4 SUSPENSION COIL

An extensive study of optimum coil geometries was carried out and reported in Reference 1. Approximate values of resistance, inductance and spacings are known, but exact physical dimensions can be to some extent arbitrary depending upon the clearance which is to be allowed between the coil windings and the specimen. This has been chosen as an arbitrary factor of 2 between average coil diameter and average specimen diameter. The number of turns in the coil can also be varied within certain limits depending upon engineering trade-offs between coil losses and transmission line losses. Numbers of turns between 1 and about 4 probably cover the feasible range. Representative coil parameters at 30 kHz are as follows.

Inductance	-	0.25 microhenries
Resistance	-	.002 ohms
Current	-	700 amps at one kilowatt
Voltage	-	33 volts at one kilowatt, 30 kHz

Voltage breakdown problems are of no serious consequence as many years of experience with terrestrial levitation furnaces indicates that with reasonable care and design arcing and sparking do not occur. One should nevertheless avoid the pressure region in the micron range favoring soft glow discharges.

At these lower frequencies the transmission line-coil loss trade-off favors three to four turns in the coil because of the relatively high currents used at the low frequencies. Going beyond three or four turns to further reduce transmission line losses is not indicated because coil conductor proximity effects begin to increase coil resistance per turn due to the redistribution of the current in each conductor under the influence of the fields of the other conductors.

As the higher resistivity specimens and correspondingly higher frequencies are considered, the coil voltages will increase due to the increase of coil reactance. Two other factors enter which cause the voltage to go much less than linearly with increase in frequency. They are the reduced requirements for current at the higher frequencies for which higher heating efficiencies are achievable and the fact that at high frequencies coils with fewer turns can be considered. As an extreme case, we can consider the zirconia example discussed in Section 5 with a 2 turn, 5 cm diameter cusp coil. Here the electrical properties of the coil will be about as follows.

Inductance	-	0.25 microhenrie
Resistance	-	approximately 0.05 ohms @ 15 mHz
Current	-	approximately 167 amps for ZrO_2 example
Voltage	-	approximately 5.6 kv at 15 mHz

The above properties are for a 2 turn (each side), 5 cm diameter cusp coil. For this case electrical breakdown between coil turns or at the coil terminals may occur. It is apparent that this problem must be studied in more detail for such extreme cases. It should be noted from Reference 1, however, that most of the examples as candidate processes lie in the lower resistivity ranges. Nevertheless, because of the highly efficient and rapid heating achievable with electromagnetic positioning it is important to determine how high in resistivity electromagnetic processing is feasible. It appears that coil electrical breakdown may prevent consideration of resistivities higher than 10^{-2} ohm-meters, even if higher frequencies are considered.

Three modifications for the zirconia experiment can be considered in the event that coil electrical breakdown is encountered for the example parameters already discussed. The first is to consider vacuum processing, which may be acceptable due to the extremely short processing times instead of a low partial pressure of oxygen, for example. A large increase in flash-over voltages can be effected in this manner. A second approach is to consider a single turn cusp coil. This will reduce the coil inductance by a factor 4, but since the required coil current is now twice as high, there is a net reduction of only a factor 2 in voltage across the coil at a fixed frequency. A third alternative is to back off somewhat on frequency and giving up a moderate amount of coil heating efficiency. The effect of a reduction in frequency by a factor 2 on heating efficiency can be seen by inspecting Figure 4-2. A decrease from 15 to 7.5 mHz would cause the heating efficiency to drop from about 80 to 65%. A 19% increase in coil current could maintain the power to the specimen constant, and so the coil voltage would be nearly halved.

6.2.5 TRANSMISSION LINE

The design of the transmission line connecting the coil to the impedance matching network and tuning capacitor is very dependent upon the frequency and layout. The most important parameter is length, due to the high currents causing losses. For 15 mHz, high voltage will be encountered and must be provided for and further, all materials of high dielectric loss must be well removed from the strong r.f. fields. These materials may not absorb a lot of power, but they are probably not cooled and could be damaged by the absorbed power. All conducting surfaces surrounding the coil, transmission line and impedance matching network such as mountings, shields, coolant hardware, etc. must be of high conductivity. Materials such as copper, brass, bronze, etc. are invariably the materials chosen for these parts. This requirement for high conductivity material is common to both high and low frequencies.

6.2.6 REACTIVE VOLT-AMPERE CORRECTION

The capacitor used for reactance correction, or tuning, is a fairly important piece of equipment in that it is highly stressed and not easily cooled. At 15 mHz, this capacitor is probably a water cooled vacuum insulated unit of about 300 pico-farads with a VAR capacity of about 10^6 volt-amperes for a 10 kw facility. Such capacitors are used in standard high frequency radio transmitters.

At 30 kHz the capacitor may be a mica unit but of a monolithic structure which might be cooled by conduction through its mounting. Industrial r.f. heating furnaces generally, but not always, use water cooled units at 10 kw and higher. Step-up transformers are used to raise the relatively low coil voltage to the high value necessary for this high energy application of mica capacitors. Volt ampere reactance in these capacitors will be about 0.2×10^6 volt-amperes at 10 kw.

6.2.7 LOADING TRANSFORMER OR NETWORK

At 15 mHz the 300 pf capacitor may not be far from directly matching the work coil, but in general some sort of network or transformer will be required for both tuning and loading. Loading is defined as matching the tuned work coil resistance to the desired load line of the power oscillator or amplifier circuit. High efficiency operation of this oscillator or amplifier circuit is strongly dependent on proper impedance matching.

The parallel impedance of the tuned coil for good conductivity specimens is much higher than for poorer conductivity specimens. To match the load to the amplifier or oscillator for both good and poor conductivity specimens simultaneously is impossible, so it may be necessary to be able to sense loading and adjust for proper match for resistivities which have extreme temperature dependence. This technique has been in use many years in communication gear and consists essentially in measuring the voltage and current ratio for oscillators. For amplifiers, it is necessary to insure that tuning is proper before matching the load, both functions being performed automatically. A common and efficient method for loading is to use switched taps on a coil or transformer. The disadvantage of this process is that it is discontinuous. Variometers are more lossy but are continuous therefore better matching can be achieved generally insuring higher overall efficiency. For modest load changes using the π network, matching could be done by switching with the cold specimen; then as the specimen heats up and its loading increases, it is accommodated using a variable capacitor also providing a continuous match and keeping efficiency up.

At low frequencies the variometer or switched taps are probably the best choice for loading.

The need for loading must be looked at carefully, particularly at the low frequencies. When the specimen is cold, it is not radiating significantly so all power absorbed goes into heating. An amplifier properly loaded for this specimen at high resistivity, will, under these conditions, dissipate more for a particular power capability, therefore it cannot deliver full power. This merely means a lengthening of the heating time somewhat. After the specimen begins to heat, its loading increases so the drive can be increased due to better matching. At full temperature and high loading, the amplifier is properly matched and delivering full power at high efficiency, thereby providing the additional heat radiation loss of the specimen. Whenever this sequence of operation is permissible, automatic loading is eliminated and complexity, weight and volume reduced and reliability enhanced.

A similar cycle to that just discussed but at 15 mHz may eliminate automatic loading. Generally, if heating at 15 mHz is employed, the same reasoning holds if the specimen's loading is adequate when it is cold or, if the specimen needs to be preheated to increase its loading.

6.2.8 RADIO FREQUENCY OSCILLATORS OR AMPLIFIERS

Probably without exception all induction heating or levitating is done by power oscillators. The additional complexity that can be introduced by the need for tuning is not necessary. For a power amplifier, the presence of the specimen fairly tightly coupled to the coil will change the reactance as well as the loading as it heats or cools, thereby detuning the output circuit and reducing the efficiency.

At 15 mHz the power oscillators for 10 kw are vacuum tube types operating with plate potentials of about 5 kv and plate currents of about 5 amps. Industrial heating practice generally uses class "C" push-pull, but some communication transmitters use one tube unbalanced for r.f. and use the same tube type in push-pull for plate modulation, thereby requiring only one tube type for spares. For our purposes the push-pull arrangement is preferred.

At 30 kHz semiconductors or tubes may be used. The advantage of semiconductors lies in the fact they can operate off the primary power bus without any power conditioning and are therefore more efficient. Tubes require power conditioning which should be done by semiconductors, so complexity is increased and efficiency is decreased. The only redeeming virtue of tubes is that with a change of reactance and impedance matching (loading) networks, the facility can operate at either high or low frequency.

The semiconductor r.f. generator is a combination of lower power units feeding the common load. Each unit i :ed at powers from 400 watts upwards to about 2 kw. Most devices are near mum under 1 kw and for 10 kw there will be at least 10 units. These multiple unit designs can be made reliable at the sacrifice of some power by allowing a unit to fail without danger to the other units which continue to deliver power. This reliability plus is very important where a fully redundant system may not be practical.

6.2.9 POWER LEVEL CONTROL

For positioning the specimen, the coil will be driven at a fixed power level sufficient to hold the specimen located adequately for the process. Such positioning power will seldom exceed a kilowatt and will not need any special level control. If the lowest level of forces are required, then the power may be considerably reduced at the expense of a greater drift distance within the coil for any given acceleration.

When electromagnetic heating is required, power may be controlled by the temperature. During the heating ramp usually full power may be applied, but when soak temperature is reached, the level must be reduced to that necessary for sustaining the temperature. This is done by controlling r.f. power with the pyrometer output.

The power output of the electron beam is best done by controlling the current because the voltage will want to be fixed by other considerations.

Controlling heating power by means of temperature sensing means a servo loop and its stability and dynamics will be heavily influenced by the specimen properties and by the highly variable radiant heat loss vs. temperature. Analytical treatment and experimental verification will have to be performed for many specimen processes to insure reasonable control of the static and dynamic temperatures of the specimen and to avoid undue interaction with position control dynamics.

6.2.10 POWER CONDITIONING FOR THE HIGH FREQUENCY R.F. GENERATOR AND THE ELECTRON BEAM HEATER

The h.f. generator will require an anode supply of about 5 kv which for good overall efficiency should be continuously variable down to approximately 1 kv. Because of cascaded losses in the conditioning equipment and the h.f. generator, it is important to have high efficiencies. To accomplish this will require considerable engineering and somewhat higher weight and volume, particularly in the power conditioning equipment.

The electron beam supply is at about 10 kv with operation possible from as low as 3 kv to higher than 15 kv. Unlike the conditioning for the r.f. unit, this voltage is not changed during the process cycle. Also, because the electron beam equipment is more efficient (practical efficiencies being about 75% for the electron beam and about 60% for r.f.), better utilization of on-board energy is possible.

Because the peak power rating is determined by the available peak power and the r.f. anode voltage is within the range required for the electron beam, it is quite possible to use only one power conditioner design for the highest power. For the sake of weight and efficiency, a smaller design might be desirable for lower power requirements.

6.2.11 OPTICAL PYROMETRY

Process temperature will have to be read remotely in all the crucibleless processes and in any process at very high temperatures.

A simple single color pyrometer has much to recommend it. If the surface emissivity is known or has been previously measured, the temperature of the specimen is easily obtained. Two single color pyrometers could be used at different colors providing the opportunity to verify or determine emissivity (if the colors are properly chosen) and providing redundancy for reliability. Such single color pyrometers are extensively used in industry and are not expensive.

The two color pyrometer is a more elaborate scheme for obtaining temperature. In operation the output of one color sensor is divided by the output of the second sensor at a different color. Thus, providing the colors and temperature range are correct, the emissivity of the source and changing properties of optical elements in the common path (mirrors, windows, vapors) have much less influence on the temperature reading. These two color pyrometers are not nearly so widely used as the single color units and one would probably have to be developed for space processing.

6.2.12 EQUIPMENT STORAGE AND OPERATING TEMPERATURES

The greatest power dissipation within the processing equipment occurs at the r.f. power units, positioning coil, and chamber. Specific processes may require high coil losses (a specimen with poor power coupling) or high chamber losses. The chamber must dissipate all the process power delivered by the r.f. unit except the coil losses (which may be small for specimens of high coupling efficiency).

The coil temperature maximum may be allowed to rise considerably over 100°C with the penalty of 30% lost coil efficiency for every 100°C rise due to the higher copper resistivity at higher temperatures. Additional considerations are the chamber penetration and viewing windows which probably will be adversely affected by the heating.

Tubes and silicon power transistors require about the same exit water temperature of 70°C. For transistors the 70°C temperature allows just sufficient thermal drop so that the junction temperature does not exceed 125°C, the highest that should be considered for reliable operation.

On the cold side, the coil is not critical but the chamber with the coil penetration and windows may not be tolerant of very low temperatures. The transistor and tube circuits are not seriously degraded at -20°C operating.

The minimum and maximum non-operating temperature of the circuits could range from about -55°C to +100°C with sufficient safeguard provided so that power cannot be applied beyond the operating temperatures mentioned earlier. Application of power at these temperature extremes may damage the power transistors or power tubes. With proper selection of material and fabrication the coast or non-operating temperature range could exceed -55°C to +100°C.

SECTION 7

EFFICIENCY, WEIGHT AND VOLUME ESTIMATES FOR ELECTRICAL EQUIPMENT

7.1 INTRODUCTION

This section is the result of a brief study by the General Electric Research and Development Center, Schenectady, N. Y. to pinpoint techniques which would be suitable for designing power supplies to operate either an electron beam gun or induction heating apparatus in space. The initial input power levels to be investigated were 10 kw and 20 kw. Of prime concern was the overall system efficiency. This assumption was used to determine that a single step conversion from battery power to supply output would be used. For example, in the case of the electron beam supply, the option of using 1800 Hz power was not analyzed due to the inefficiency and weight penalties attendant with generating a three phase 1800 Hz bus and then transformation at that frequency.

This effort is a minimal summary of the ideas generated inhouse as well as a limited search of the literature. Considerable use of the literature was employed to substantiate weight and volume projections. It became obvious during the investigation that the achievable size and weight would be strong functions of the amount of engineering effort applied to fabricating the power circuitry involved. Considerable space and hardware can be saved if full use of advanced power hybrid technology is employed in the fabrication of these circuits.

7.2 ELECTRON BEAM SUPPLY

7.2.1 Assumptions: The major assumptions upon which this study was based are given below.

7.2.1.1 Primary source of power will be fuel cells (supplemented by batteries).

7.2.1.2 Overall efficiency is a high priority item.

7.2.1.3 Redundancy or fail-safe design would be desirable.

7.2.1.4 Load short circuits will occur.

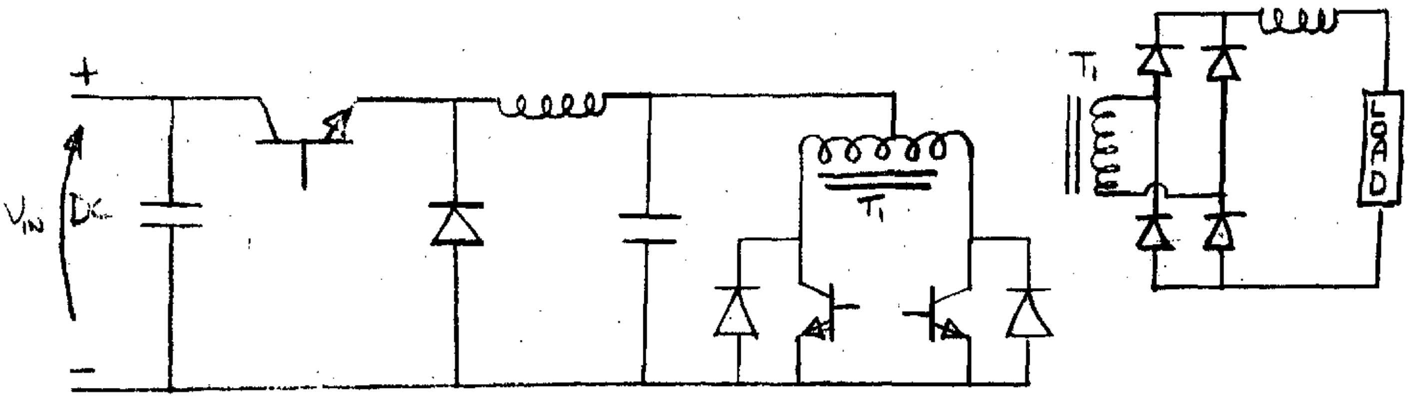
7.2.1.5 Power supply voltage and current are to be controlled.

7.2.1.6 Batteries may be connected in series to provide higher input voltages.

7.2.2 CIRCUIT APPROACHES

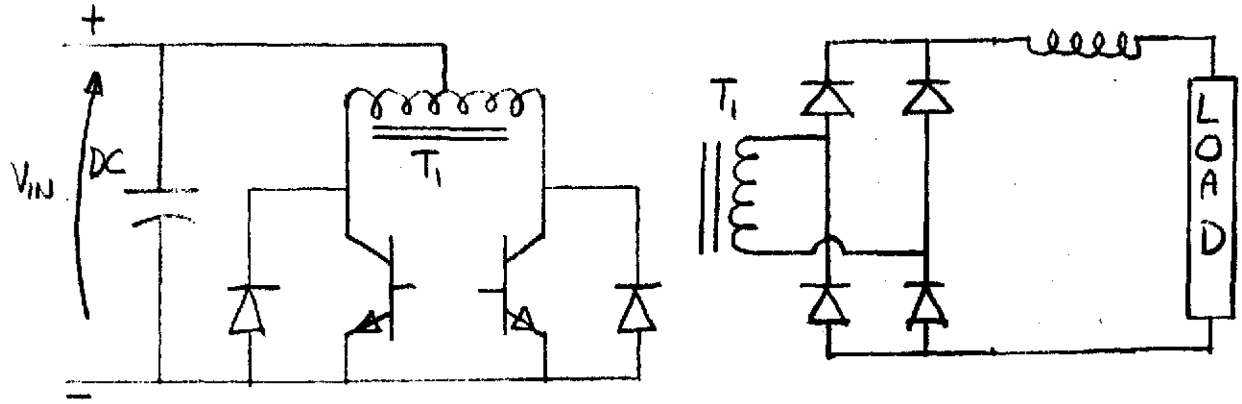
7.2.2.1 Introduction

Three circuit approaches were considered as shown in Figures 7-1a, b and c. These are the preregulated transistor inverter, self-regulated transistor (SRT) inverter and preregulated self commutating series commutated SCR inverter in half bridge or full bridge configuration. Since one of the major assumptions (7.2.1.2) pinpoints overall efficiency as a major element of this study, methods requiring preregulation have been ruled out as too costly in terms of efficiency. At these input voltages it is difficult to conceive of a preregulator with an efficiency greater than 95% with 92-94% mor typical of step down regulators. Step-up systems may be as low as 90-93% efficient. The SCR circuit would most definitely require a step-up preregulator, while the transistor approach could use a step down system. However, the attendant reduction of the supply voltage will require more effort to retain a highly efficient inverter section in that case.



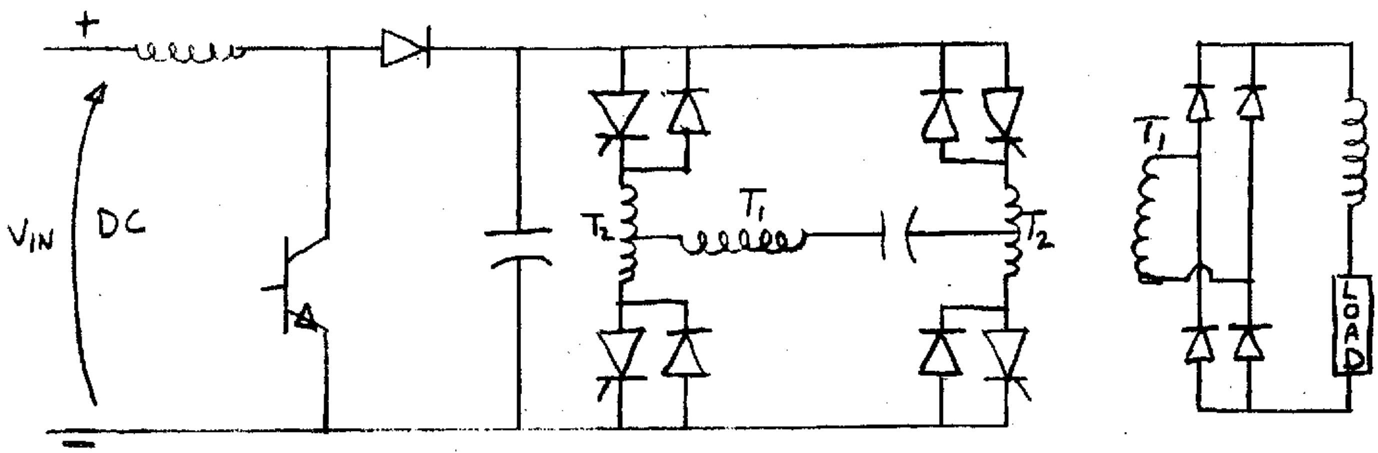
PREREGULATED TRANSISTOR INVERTER

Figure 7-1a



SELF-REGULATED TRANSISTOR (SRT) INVERTER

Figure 7-1b



PREREGULATED SERIES COMMUTATED SCR INVERTER

Figure 7-1c

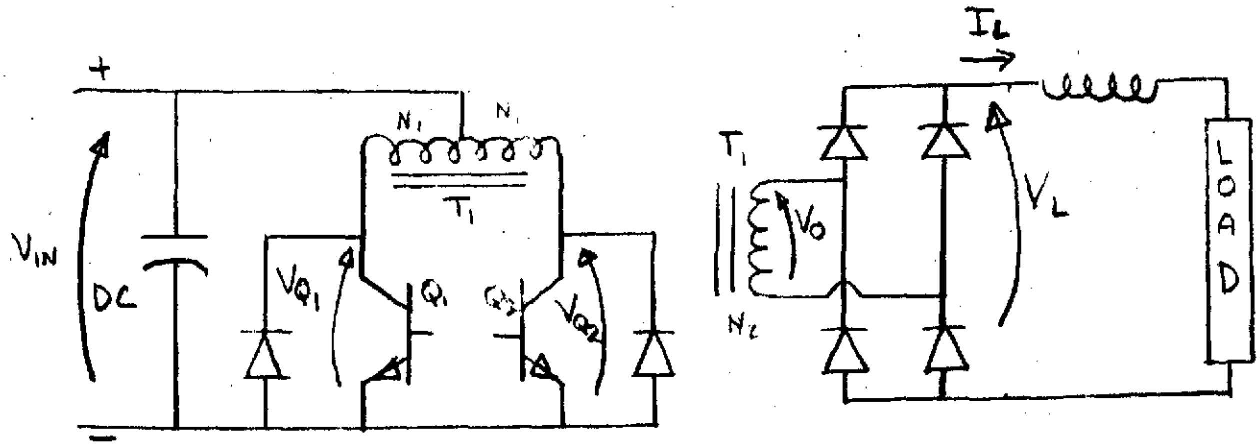
For these reasons the self-regulating transistor inverter was investigated in more detail.

7.2.2.2 Self-regulating Transistor (SRT) Inverter

7.2.2.2.1 Introduction - The basic SRT circuit and waveforms are shown in Figures 7-2a and b. This circuit was studied in detail. Briefly the circuit is a driven push-pull inverter which operates in a pulse width modulated mode. That is, during the time t_2-t_3 and t_4-t_5 neither transistor Q_1 or Q_2 is conducting. Due to the free-wheeling current in the load, the transformer output is clamped to zero by the action of the output rectifier diodes. Therefore by varying the dwell time in this condition, the output voltage can be regulated at some value below that determined by the input voltage and transformer turns ratio. This achieves the same function as a preregulator and square wave inverter in one power handling step instead of two. The technique is particularly useful with back emf loads.

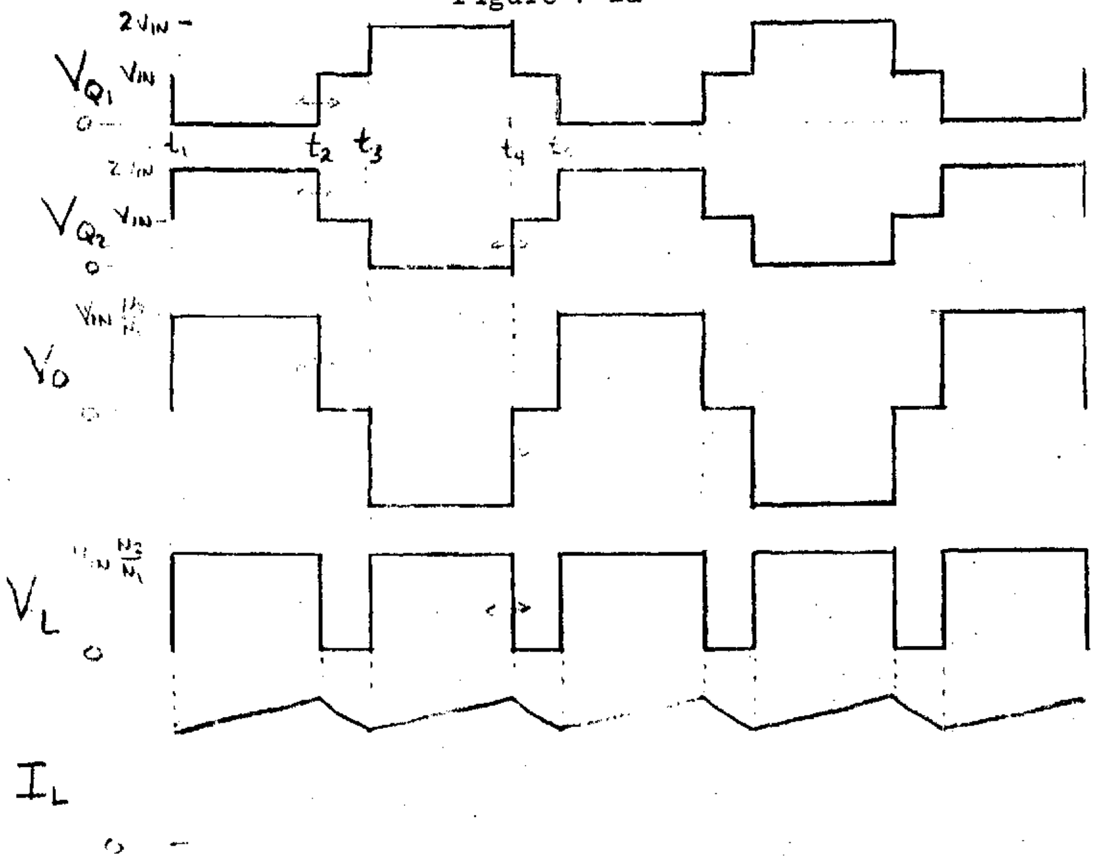
7.2.2.2.2 Calculated Data for the SRT Inverter - The SRT inverter circuit was analyzed to determine the stresses placed on the various components. These stresses are summarized in Table 7-1a, b and c.

Figures 7-3a and b show the two basic configurations analyzed. The analysis was carried out at two input power levels as assumed in this report (10 KW and 20 KW). It was also calculated in accordance with assumption 2.1.6 that the input voltages were 25.5-32 V, 51-64 V, 102-124 V due to battery seriesing. The calculation procedure is not given here. The circuit of Figure 7-3a shows a single SRT inverter with multiple rectifiers to reach the level of 12 KV. These rectifiers need to be fast recovery types which are not available as single units in 12 KV ratings. The rectifiers must therefore be assemblies of rectifier pellets. Common



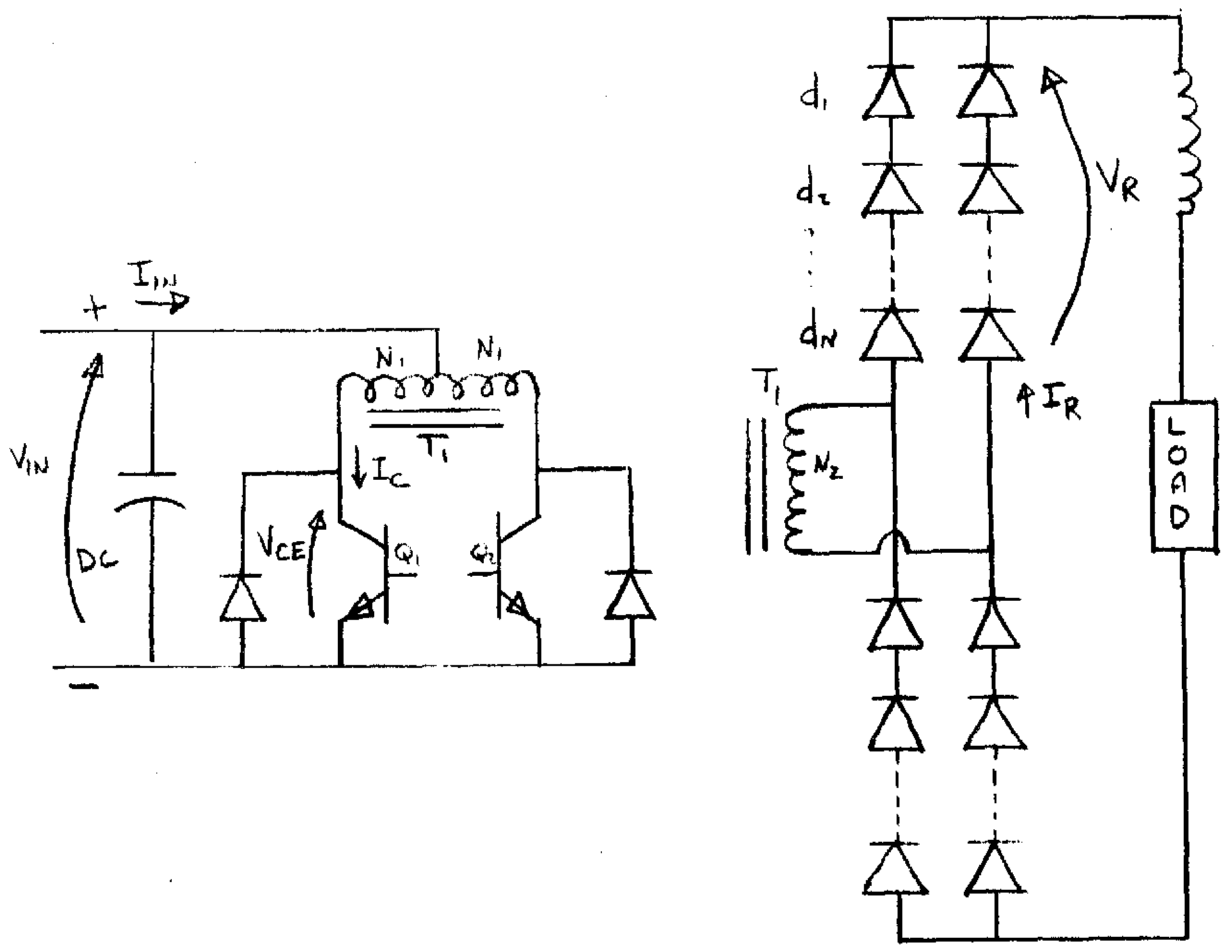
SRT INVERTER & LOAD

Figure 7-2a



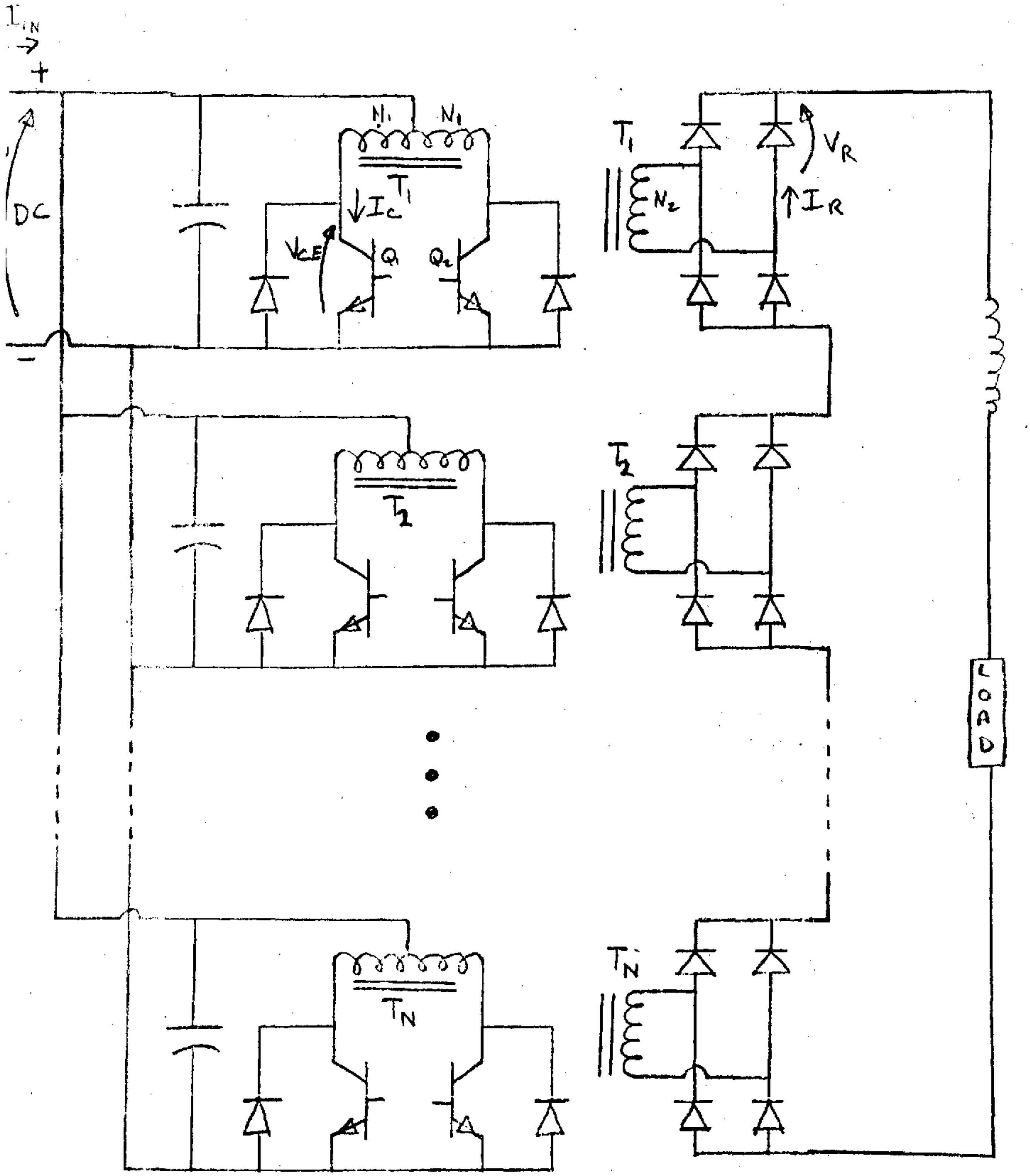
SRT INVERTER WAVEFORMS

Figure 7-2b



SINGLE SECTION SRT INVERTER CIRCUIT

Figure 7-3a



MULTICYLINDER ELECTRON BEAM SUPPLY

Figure 7-3b

C.2

Table 7-1a

SRT Inverter Device Rating Summary

INVERTER SECTION										OUTPUT SECTION			
V_{IN} (V)	I_{IN} (A)	P_{IN} (KW)	Number of Inverters	V_{CE} (V)	I_C	P_{LOSS} (W)	Transformer Rating (KW)	Total Number of Transistors	$V_{CE_{SAT}}$ (V)	$\frac{N_2}{N_1}$	P_{OUT} (KW)	I_R (A_{peak})	V_R (KV
25.5	400	10	1	128	431	905	9.4	2	.7	500	8.5	.78	16
25.5	800	20	1	128	860	1.8K	18.2	2	.7	500	16.9	1.5	16
25.5	400	10	5	128	86.2	517	9.7	10	.4	100	8.7	.79	3.2
25.5	800	20	5	128	172	1.3K	19.1	10	.5	100	17.3	1.5	3.2
25.5	400	10	10	96	43	387	9.6	20	.3	50	8.6	.79	1.6
25.5	800	20	10	128	86	1.0K	19.0	20	.4	50	17.1	1.57	1.6
25.5	400	10	25	96	17.2	387	9.6	50	.3	20	8.6	.79	.64
25.5	800	20	25	96	34.5	774	19.2	50	.3	20	17.3	1.6	.64
25.5	400	10	50	96	8.6	387	9.6	100	.3	10	8.6	.79	.32
25.5	800	20	50	96	17	774	19.2	100	.3	10	17.3	1.6	.32

Table 7-1b

SRT Inverter Device Rating Summary with $V_{IN} = 51V$

V_{IN} (V)	P_{IN} (KW)	I_{IN} (A)	Number of Inverters	V_{CE} (V)	I_C (A)	P_{LOSS} (W)	Transformer Rating (KW)	Number of Transistors	$V_{CE_{SAT}}$ (V)	$\frac{N_2}{N_1}$	P_{OUT} (KW)	I_R (A_{peak})	V_R (KV)
51	10	200	1	256	220	420	9.6	2	.7	250	8.7	.79	16
51	20	400	1	256	440	840	19.1	2	.7	250	17.2	1.57	16
51	10	200	10	192	22	240	9.7	20	.4	25	8.7	.8	1.6
51	20	400	10	192	44	600	19.4	20	.5	25	17.5	1.61	1.6
51	10	200	25	192	8.8	240	9.7	50	.4	10	8.7	.8	.64
51	20	400	25	192	17.6	480	19.5	50	.4	10	17.6	1.62	.64

Table 7-1c

SRT Inverter Device Rating Summary with V_{IN} = 102V

V_{IN} (V)	P_{IN} (KW)	I_{IN} (A)	Number of Inverters	V_{CE} (V)	I_C (A)	P_{LOSS} (W)	Transformer Rating (KW)	Number of Transistors	$V_{CE_{SAT}}$ (V)	$\frac{N_2}{N_1}$	P_{OUT} (KW)	I_R (A_{peak})	V_R KV
102	10	100	1	512	110	330	9.6	2	1.1	125	8.6	.79	16
102	20	200	1	512	220	720	19.2	2	1.2	125	17.3	1.58	16
102	10	100	10	384	11	270	9.7	20	.9	13	8.7	.8	1.6
102	20	200	10	384	22	540	19.4	20	.9	13	17.5	1.6	1.6
102	10	100	25	384	4	240	9.7	50	.8	5	8.7	.8	.64
102	20	200	25	384	8	540	19.4	50	.9	5	17.5	1.6	.64

practice is to use controlled avalanche breakdown rectifiers in applications such as these to guarantee the voltage sharing function in high voltage stacks. It became apparent that the input current levels in this application were becoming quite excessive (>600A). Therefore the multicylinder approach of Figure 7-3b where a plurality of SRT inverters can be operating in parallel at lower current and output voltage levels than the single inverter was investigated. The inverter outputs would be seriesed as shown to produce the necessary voltage for the gun. A system of this general approach (with pre-regulator, however) is shown in the 1971 PCSC Record, but is not reproduced here. It has been shown that stagger firing of the inverter circuit can significantly reduce the amount of filtering necessary both at the output and input of such a system.

7.2.2.2.3 Conclusions on the SRT Inverter - The multicylinder SRT inverter approach to the electron beam supply will result in a high degree of reliability for the following reasons. The redundancy achieved will allow the system to operate with one or more inverters inoperable. Secondly, it is possible to eliminate the matching networks and transistor selection necessary for the construction of one single inverter requiring parallel power transistors to achieve the necessary current rating. Third, the filament supply can be a module identical to the beam power modules if the proper wattage modules are utilized.

7.3 INDUCTION HEATING SUPPLY

7.3.1 Assumptions: The following assumptions were added to those of Section 7.2.1 on the Electron Beam Supply.

7.3.1.1 The load coil current may be 800A rms.

7.3.1.2 Coil is only 20% efficient or has a Q of 5 when the sample is in place.

7.3.1.3 The high reactance loads will dictate pseudo sinewave operation resulting in higher peak currents for a given load.

7.3.1.4 A separate matching transformer and tuning capacitor will be required at the load coil to reduce transmission line losses.

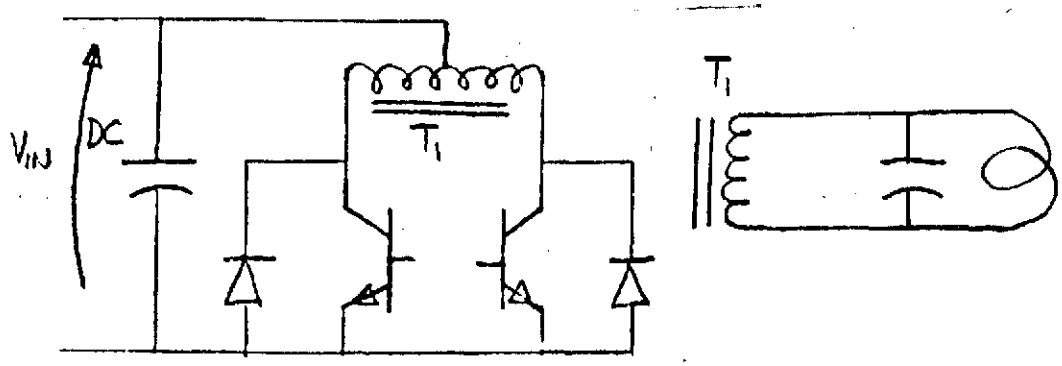
7.3.2 CIRCUIT APPROACHES

7.3.2.1 Introduction

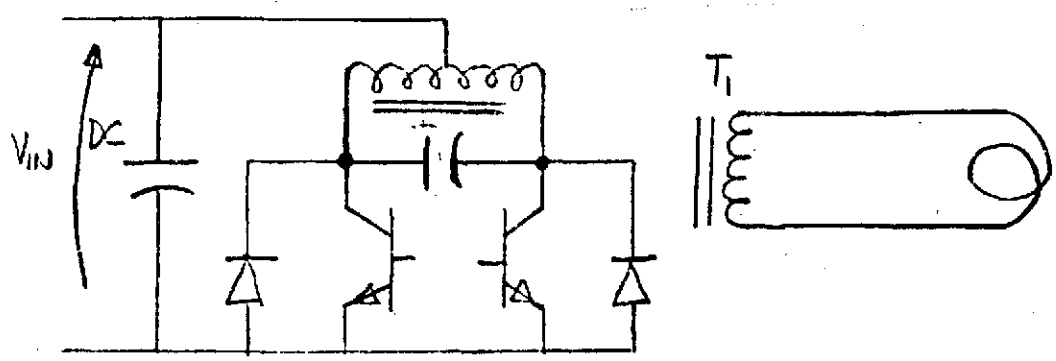
Following the same format as Section 7.2 on the electron beam supply, it was decided to focus attention on an SRT inverter with the possibility of a multicylinder approach for the induction heating supply. However, in this case stagger firing is not possible and synchronized operation is a necessity to allow proper summation in the matching transformer. The use of multiple inverters again is quite significant in that the transmission line loses from power conditioner to matching transformer may be minimized by utilizing a finite sized litz wire transmission line. This can be accomplished by suitable choice of impedance levels.

Figure 7-4 a and b shows the two commonly used methods of drive coil tuning in the push-pull inverter case. The figure a case where the transformer output is capacitively tuned requires a capacitor of high current rating. However, the figure b case using transformer input tuning requires the transformer to carry the full

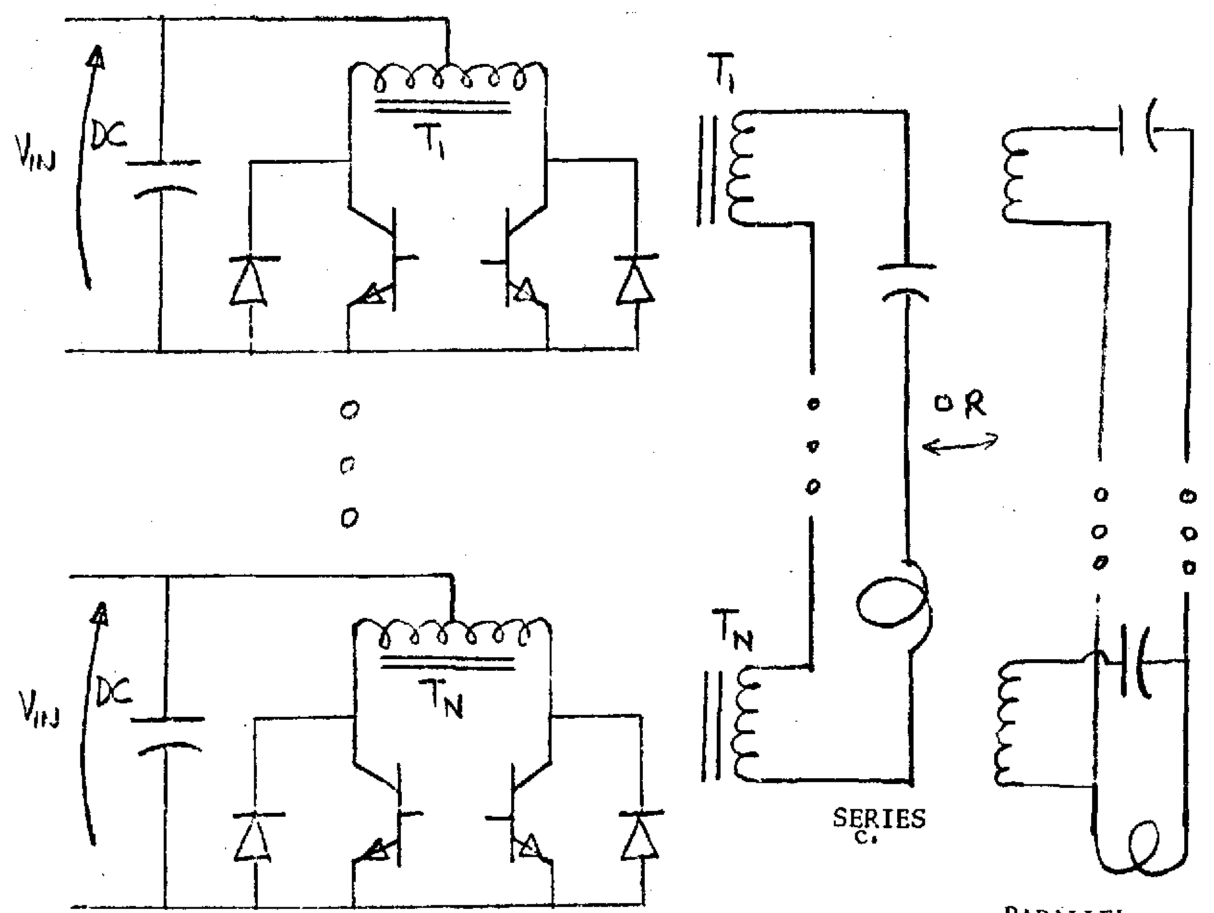
Figure 7-4



a. PARALLEL TUNED OUTPUT



b. INPUT TUNED



SERIES
c.

PARALLEL
d.

MULTICYLINDER INVERTER

volt-amperes of the drive coil. Whereas, at high frequencies this can be accomplished with little overall weight penalty since the capacitor has a much lower current rating, at the VLF frequencies dealt with in this report this technique would add a severe weight penalty due to the increased transformer weight. For this reason the method of figure b was not investigated further.

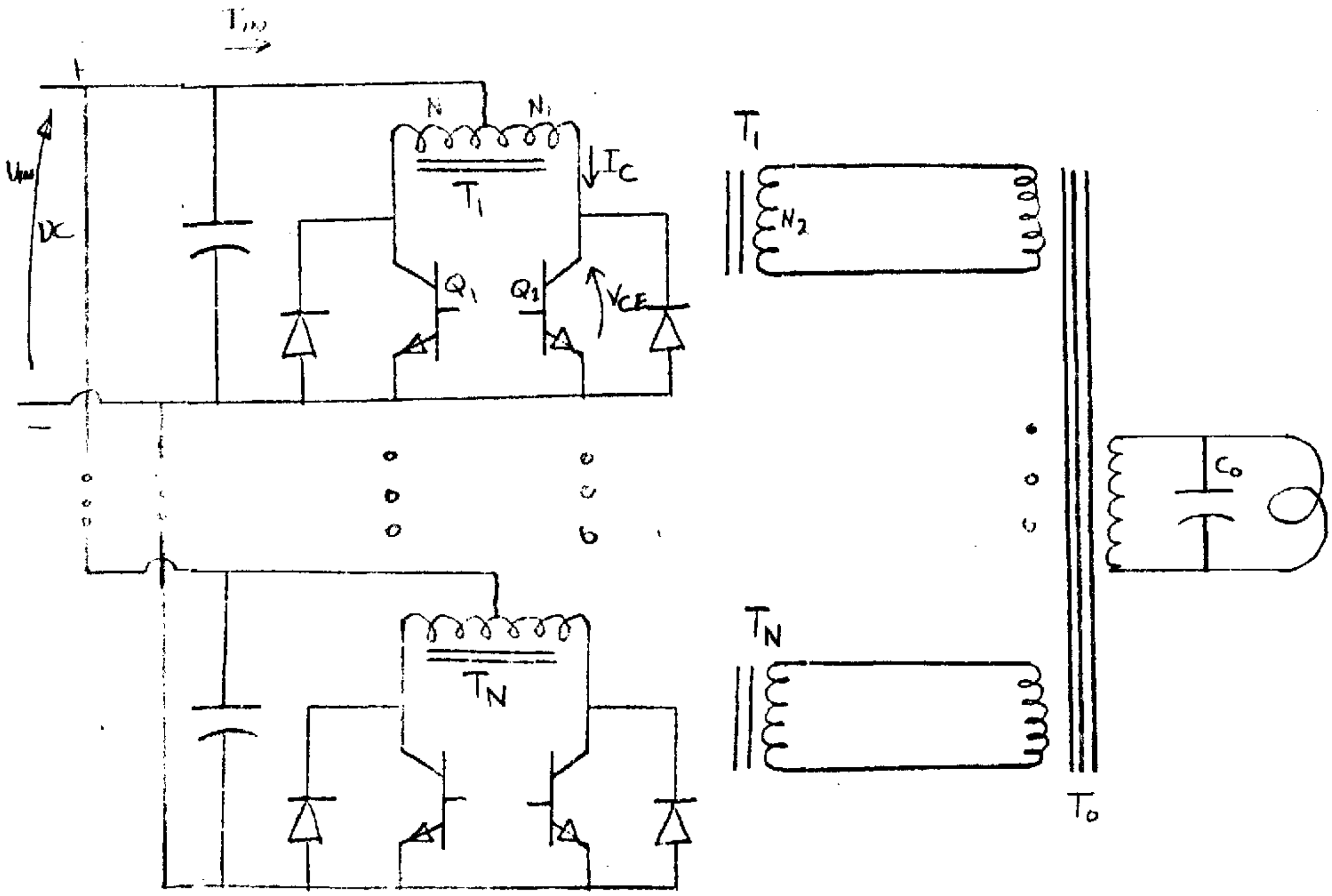
Figure 7-4 c and d are typical circuits which could be used to directly couple to the drive coil from a multiple inverter system. Figure 7-4c adds the output currents in series. This approach can be discarded since any inverter failure will render the system inoperable. The heavy currents required in each output transformer would also strain the capability of the designer to arrive at a light-weight system. The parallel output scheme of figure d will satisfactorily operate the drive coil from a multiplicity of inverters. However, the effectiveness of the multiple capacitor tuning is doubtful. At full power there is little doubt that this approach would work. Since the supply is to be operated at significantly lower levels also, it becomes apparent that a partial reduction in output would cause the output tank circuit to become untuned. This would be an unsatisfactory condition and is to be avoided. Therefore the system of figure d was discarded.

Figure 7-4e is a diagram of the circuit deemed most likely to perform adequately over the range of frequencies 10-100kHz. The output transformer T_o and capacitor C_o can be mounted remotely from the power conditioner with its multiplicity of inverters and push-pull transformers T_1-T_N. It should also be possible to utilize a sufficiently high impedance level to minimize the transmission losses to the experiment transformer T_o.

7.3.2.2 Calculations

The circuit was analyzed in considerable detail. These calculations were merely extensions of those mentioned previously on the electron beam supply circuit. The assumption that the circuit will operate into a non-resistive load increases the instantaneous currents in the transistor by a factor of $\sqrt{2}$ over the pure square wave back emf case. The results of these calculations are given in Table 7-2.

One comment should be made concerning the transistor losses. In particular it can be seen that high values of saturation voltage were given to the high current transistors. Whereas it is well known that transistors exist with much lower drops than those shown, the high current cases will necessitate some device paralleling. The resulting current sharing networks usually add a significant amount of loss to the overall system. This loss has been lumped into the saturation drop with lower values for lower amounts of collector current since the sharing networks will have less function at low current levels.



PARALLEL SRT INDUCTION HEATING CIRCUIT

Figure 7-4e

Table 7-2

Induction Heating Supply

V_{IN}	P_{IN}	Number of Inverters	I_C	V_{CE}	$V_{CE_{SAT}}$	P_{LOSS}	$\overline{P}_{XMER}$ (KW)	Number of Transistors	P_{XMER} (KW)
25.5	10	1	554	90.5	.7	387.8	9.7	2	9.7
	20	1	1109	90.5	.8	887	19.2	2	19.2
25.5	10	10	55.4	90.5	.4	221.6	9.8	20	.98
	20	10	110.0	90.5	.5	554	19.5	20	1.95
25.5	10	30	18.5	90.5	.3	166	9.8	60	330W
	20	30	36.9	90.5	.3	332	19.7	60	660W
25.5	10	60	9.22	90.5	.3	166	9.8	120	165W
	20	60	18.47	90.5	.3	332	19.7	120	330W
51	10	1	277	181	.6	166.2	9.9	2	9.9
102	10	1	138.5	362	.5	69	9.9	2	9.9

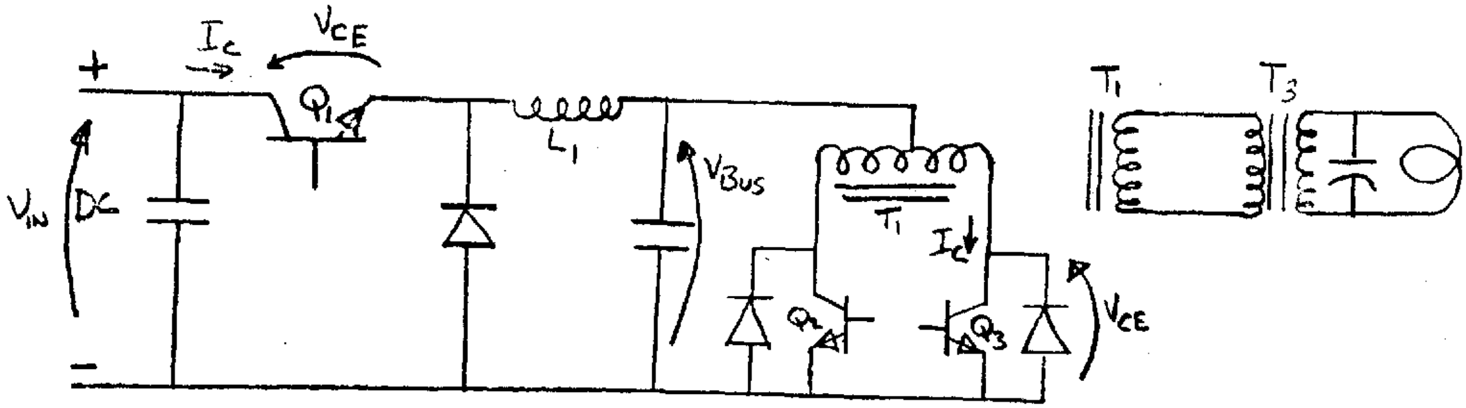
7.4 LOW POWER INDUCTION POSITIONER

7.4.1 ASSUMPTIONS: The low power induction positioner will be necessary to contain the experiments which have been heated using the electron beam gun. The following assumptions in addition to those already assumed for the electron beam supply are given below.

7.4.1.1 A matching transformer will be used external to the supply and the load will be parallel tuned at the drive coil. This is not a necessary condition; however, the calculations will be based on a resistive reflected load. For other systems the reactive component must be taken into account as well.

7.4.1.2 Power must be precisely controlled all the way to zero output. This will necessitate an additional power handling stage.

7.4.2 INTRODUCTION: Power supplies of this type are common in the art. The mentioned paper on page 110 of the 1971 PCSC Record deals in detail with the class of circuits shown in Figure 7-5.
The circuit employs a chopping mode preregulator to establish a DC bus voltage which is variable from zero to 90% of the minimum input voltage. This preregulator can operate at a relatively low frequency to enable a wide range of chopping control. The output inverter is operated at the frequency dictated by the sample and coil design. These inverters may be self excited with the proper current feedback windings on the transformer or of the driven base design with integrated circuit logic and base drivers.



LOW POWER INDUCTION POSITIONER

Figure 7-5

7.4.3 CALCULATIONS

The specific circuit calculations are not reproduced here but are summarized in Table 7-3. It can be seen that this supply can be accomplished with quite standard components without resorting to paralleling techniques.

Table 7-3

		Q_1 & Q_2		Q_3		
P_{out}	V_{Bus}	V_{CE}	I_C	V_{CE}	I_C	Weight
100W	23V	65V	7.5	48V	6.5	4-5 lbs

7.5 CONDITIONER WEIGHTS AND SIZES

7.5.1 INTRODUCTION

A number of possible sources for projected weights are available. The specific weight and size will be a function of the overall efficiency specifications and system division philosophy followed. Figure 7-6a is reproduced from the IEEE Transactions on Aerospace and Electronic Systems, 1971, Vol. AES7, Number 6, page 1192, while Figure 706b and 7-6c are found on page 1191. The complete paper is readily available. Figure 7-6a shows graphically that for a system similar to that of the electron beam supply the weights will be a strong function of the overall specified efficiency. Figures 7-6b and c show the dependence of weight on overall power level and the operating frequency respectively. Figure 7-6b can be used to calculate the lbs/KW factor as a function of inverter power rating for a preregulated supply. Table 7-4 has been compiled in this way.

Figure 7-6a

Conditioner weight as a function of efficiency.

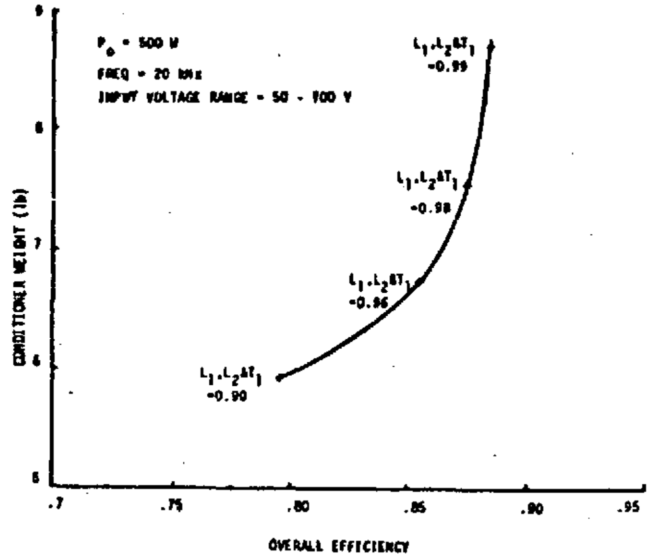
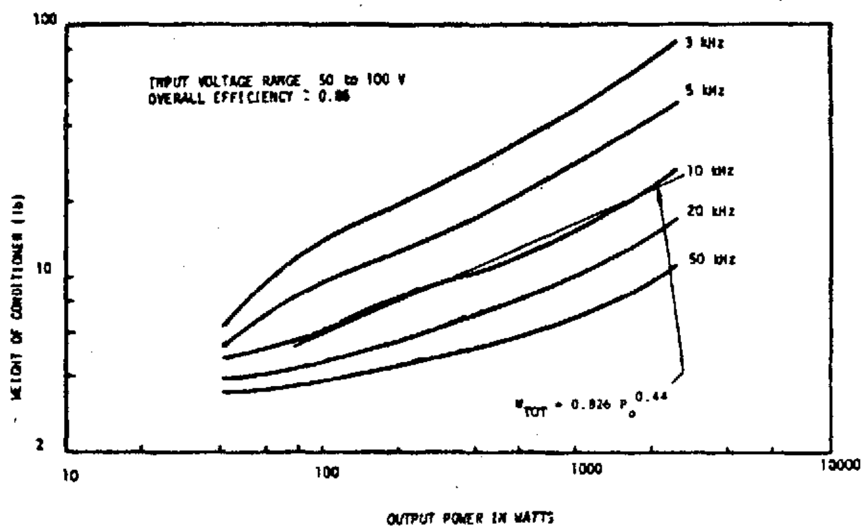


Figure 7-6b



Conditioner weight as a function of output power.

Figure 7-6c

Conditioner weight as a function of frequency.

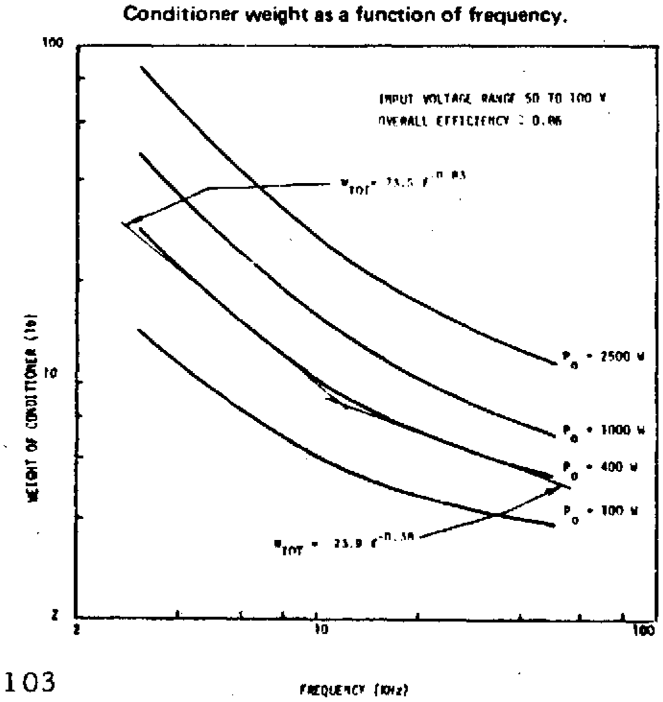


Table 7-4

lbs/KW for Preregulated Supply

P_{out}	50KHz lbs/KW	20KHz lbs/KW
100	39	47
200	22	28
400	12.7	17.5
1000	7	10
2000	4.75	7

It is obvious that this data would indicate that the subdivision into a plurality of inverters should be kept small. It should be noted, however, that the calculated data refers to a much more complicated circuit than is proposed. Using these numbers and others which are known, the specific self regulated supply weights can be calculated.

7.5.2 ELECTRON BEAM SUPPLY

7.5.2.1 Weight

The choice of the SRT inverter circuit was made for a twofold purpose. The first was the efficiency factor which has been discussed. The second factor was the simplicity of power processing. Only two transistors instead of three are used. Also, only one magnetic component is used instead of two. A rough approximation then would be that the weight of this system could be as little as .6 of the weight as given in Table 7-4. A conservative estimate would be .75 of the Table 7-4 figures. These are listed in Table 7-5 below.

Table 7-5

lbs/KW for SRT Inverter System

P_{out}	50KHz lbs/KW		20KHz lbs/KW	
	min.	max.	min.	max.
100	23.4	29.25	28.2	35.25
200	13.2	16.5	16.8	21
400	7.6	9.525	10.5	13.1
800			8.3	
1000	4.2	5.25	6	7.5
2000	2.9	3.6	4.6	5.25

The number 8.3 lbs/KW entered at 800 watts output is an independent check arrived at by weighing the SRT power converter built in this laboratory. It is felt that this is a conservative figure since air cooling was used and no significant attempt was made to minimize weight in the construction of that system. Also, the low voltage output was controlled by a circuit breaker and heavy copper wire which would not be applicable in a high voltage application. Therefore, it can be seen that the .6 factor used in Table 7-5 is conservative.

An accurate estimate for the weight of the SRT inverter supply would be dependent on the number of submodules chosen. Tables 7-6a and 7-6b give the module size vs. overall weight of the SRT inverter systems at 10 KW and 20 KW respectively.

Table 7-6a

10KW SRT Inverter Weight for Electron Beam Supply

Operated at 20-25KHz

Number of Modules	Power per Module (W)	Peak Transistor Current (A)	Overall Weight (lbs)
5	2000	88	46 - 52
10	1000	44	60 - 75
13	800	33.8	83 - 103
25	400	17.6	105 - 131
50	200	8.8	168 - 210

Table 7-6b

20KW SRT Inverter Weight for Electron Beam Supply

Number of Modules	Power per Module (W)	Peak Transistor Current (A)	Overall Weight (lbs)
10	2000	88	92 - 104
20	1000	44	120 - 150
26	800	33.8	166 - 206
50	400	17.6	210 - 262
100	200	8.8	336 - 420

7.5.2.2 Size

The conditioner size is quite obviously a function of the amount of engineering time available to package the inverter as well as magnetic material size. The same basic conclusions which were discussed with regards to weight and module power output can be developed for the module size considerations. The size of the overall converter will depend strongly on the methods used to produce the high voltage winding on the module output transformers as well as the high voltage rectifier stack.

7.5.2.2.1 Transformer

The transformer can be produced with a solid encapsulant. At this time, this technology is not far advanced beyond being an art. However, it has been demonstrated by Hughes in Paper 1.4 at the 1974 Power Electronics Specialists Conference that a solid encapsulant can be used for space environment and high voltage. Their size for a 400W, 10KHz transformer was 16 in^3. Assuming a factor of 2 improvement by going to 20-25KHz would yield a transformer of 20 in^3/KW at the 400 watt level. Our own designs without the solid encapsulants yield 12.54 in^3/KW at the 800W level. Therefore, a compromise number of 15 in^3/KW would seem reasonable for the 1KW and below wattage levels.

7.5.2.2.2 Transistor Circuitry

If chill block cooling is used, the power devices would need very little space if mounted in a hybrid package. Standard transistor packages would present a severe size penalty. Whereas hybrid packaged inverter transistors and reverse diodes may take up as little as 1 in^3 including the chill plate the conventional hermetic packaged devices (TO 3) would take 3.5 in^3 for 25-40 ampere transistors. These devices could be used in a module rated up to 1KW at the 25.5V input voltage.

It can be seen then that a properly designed hybrid module can reduce the overall size considerably. The technology exists within the company to directly apply copper to dielectrics such as Alumina or BeO. These Cu-BeO-Cu sandwiches can then be etched as any other printed circuit to provide high conductivity paths for hybrid circuits. A second advantage of this technology is the reduction of lead lengths and subsequent reduction in energy stored in the lead inductance which must be dissipated by the switching transistors.

The base drive requirements can be met in three ways. The first method would employ feedback windings on the output transformer to produce positive and negative supplies for the base drive circuitry. An alternative mode would be to employ a current transformer linked to the transistor collector so that a base drive current proportional to collector current is available. The third method was used in the 50 ampere converter built in this laboratory. A small inverter was used to supply the base drive to the transistors. In that circuit it was also possible to use a Darlington power transistor configuration. This further reduced the power required of the base drive circuit. It is assumed that the base drive supply for each module could be fabricated in 2 in^3.

7.5.2.2.3 High Voltage Rectifier

The high voltage rectifier stack will be fabricated of a number of discrete rectifier pellets. At this time a conservative figure of 400V is what is available in high speed avalanche breakdown devices. Therefore, a full bridge would use a total of 4x(12KV/400) or 120 rectifiers with no voltage margin. A more realistic number would be 40 per leg for a capability of 16KV or 160 devices. If these devices are not encapsulated in a solid system, they will need to be insulated by some fluid or gas means.

Again, the overall size will depend on the choice of packaging technique. It is proposed to package the rectifier stack using a hybrid package. The diode pellets could be put down on an Alumina or BeO substrate which would be cooled by the chill plate. A size for this assembly if solid filled would be 3 in x 1 in x .5 in for a volume of 1.5 in^3. If the output stack is constructed of packaged devices in an oil filled container, then the size might be as large as 5 in long by 1 in diameter for a total of 4 in^3. A gas cooled stack would be even larger and may necessitate an enclosed fan to circulate the gas over the rectifiers and to the chill plate. The size of a gas filled system may be as large as 70 in^3.

7.5.2.2.4 Logic Circuitry

It is assumed that maximum utilization of integrated logic would be used in this system. Without resorting to MSI or custom circuits the logic for the entire converter should be packaged in a box 5 x 7 x 5 for a total size of 175 in^3. Multilayer circuit boards and some custom IC utilization should be able to bring this down to a 2.5 in high box for a total area of 88 in^3. Further reduction in size might be accomplished by use of thick film hybrid circuit fabrication techniques.

7.5.2.2.5 Wiring and Filter Components

The output surge limiting resistor may take up 2 in^3 if not done in hybrid form as is done in the television industry.

The wiring space factor will be a function of which methods of transistor packaging are used and which output rectifier method is used. For the more compact planar approaches which can be packed more efficiently, a number of .8 may be sufficient. The larger less regular subsystems may only pack to a factor of 1.5. Therefore, the subsystem totals may be multiplied by a factor of 1.8 for compact subsystems and 2.5 for less regular subsystems to derive the overall system size.

The filter components would take up considerable room. However, the use of stagger firing may significantly reduce the filter requirements. Two estimates would be 10 in^3 for a reduced filter and 15 in^3 for a full filter size per 1KW module.

7.5.2.2.6 Size Conclusion

The overall size will depend on the number and size of the submodules chosen. Table 7-7a shows the size for a 10 KW input system with 10 1KW subsystems. Table 7-7b shows the same submodules in a 20KW system. Similar tables can be constructed for other submodule sizes.

The total size in this case would be between 670 and 1620 in^3 at 10KW for a spread of 67-162 in^3/KW. The spread at 20KW would be 59-131 in^3/KW. Therefore, it can be seen that larger power converters are more economical of size as well as weight on a per KW processed basis.

Table 7-7a

Power Converter Size 10KW Input

	Component Size small (in^3)	Component Size large	Number of Components	Total Space (in^3) min.	Total Space (in^3) max.
Transistors	1	3	10	10	30
Transformers	15	20	10	150	200
Base Drive	2	2	10	20	20
Output Rectifier	1.5	70	1	1.5	70
Logic Box	88	175	1	88	175
Surge Resistor	2	2	1	2	2
Filter Components	10	15	10	100	150
Wiring Space Factor	.8	1.5		297	970
TOTAL SPACE				668.5	1617

Table 7-7b

Power Converter Size 20KW Input

	Component Size small (in^3)	Component Size large	Number of Components	Total Space (in^3) min.	Total Space (in^3) max.
Transistors	1	3	20	20	60
Transformer	15	20	20	300	400
Base Drive	2	2	20	40	40
Output Rectifiers	1.5	70	1	1.5	70
Logic Box	88	175	1	88	175
Surge Resistor	2	2	1	2	2
Filter Components	10	15	20	200	300
Wiring Space Factor	.8	1.5		521	1570
TOTAL SPACE				1172.5	2617

7.5.3 INDUCTION SUPPLY

7.5.3.1 Introduction

The induction supply size and weight will be a function of the lowest desired operating frequency. Since the magnetic structures are volt-second limited, their physical size must be increased as the operating frequency is decreased. The input filter components will likewise need to be increased in size as the frequency is decreased. For this reason it is difficult to predict an overall size and weight for the induction supply.

7.5.3.2 Weight

Again it is possible to draw conclusions from the calculations performed for the electron beam supply. If the data of Figure 7-6c is extrapolated to 100KHz and tabulated to show the amount of conditioner weight as a function of frequency and module size the data of Table 7-8a results.

Table 7-8a

Pre-regulated Inverter Weight vs. Frequency

Frequency of Operation (KHz)	Inverter Output Power				
	100W	400W	1000W	2500W	
10	60	25.0	15.5	10.4	Weight (lbs/kw)
20	46	17.8	10.5	7.0	
40	40	14.0	7.5	5.0	
60	36	12.8	6.7	4.4	
80	35	12.4	6.1	4.2	
100	34	12.0	6.0	3.9	

To arrive at a predicted weight for the induction supply, the assumption about a matching transformer must be invoked. The weight of the conditioner will be calculated exclusive of the final matching transformer which will be an integral part of the drive coil assembly to minimize transmission losses. Therefore, it is appropriate to apply the weight ratios of .5 and .7 for possible and conservative weights since the converters will not have an output rectifier. The resulting overall weight may be seen in Table 7-8b. It must be remembered that the weight of the matching transformer must be added to this weight for a complete estimate.

Table 7-8b

SRT Conditioner Weights vs. Minimum Frequency of Operation

Overall Weight of Conditioner for 10KW Input

Minimum Freq. of Operation (KHz)	100W 100 min	max	400W 25 min	max	1000W 10 min	max	2500W 4 min	max	Module Size / No. of Modules
10	300	420	125	175	77	108	52	72	Weight (lbs/kw)
20	230	322	87	122	52	73	35	49	
40	200	280	70	98	37	52	25	35	
60	180	252	64	89	33	46	22	30	
80	175	245	52	86	30	42	21	29	
100	170	238	60	84	30	42	19	27	

In conclusion, then, the converter could weigh as little as 80 lbs and operate from 10KHz to 100KHz if 10 modules of 1KW size were used. Again, a word of caution should be injected. These numbers have been arrived at by assuming that relatively conventional circuit construction would be employed. If extensive use was made of power hybrid modules the weights might be significantly lower. Also if very high efficiency is to be expected (>85%), then a weight penalty will be paid.

7.5.3.3 Size

7.5.3.3.1 Introduction

The components used in the conditioner can be divided into two categories. First, there are those components which do not vary in size as a function of frequency and secondly, those that do. Also, the sizes calculated for the electron beam supply can be used in many cases.

7.5.3.3.2 The Frequency Invariant Components

The transistors, base drive supplies and control logic box are all frequency invariant. These units can be assumed to be the same size as the components in the electron beam supply sub-modules. For a 10KW and 20KW conditioners utilizing 1KW modules the size of these components is given in Table 7-9 below.

Table 7-9

Frequency Invariant Component Sizes

	Component Size (in^3) small	large	Number of Components at 10KW	Size at 10KW (in^3) min	max	Number of Components at 20KW	Size at 20KW (in^3) min	max
Transistors	1	3	10	10	30	20	20	60
Base Drive	2	2	10	20	20	20	40	40
Logic Box	88	175	1	88	175	1	88	175
TOTAL SIZE (in^3)				118	225		148	275

7.5.2.2.2 Frequency Dependent Components

The transformers and input filters are the major size dependent components. The transformers may be as large as 2.5 times the electron beam size at 10KHz and as small as .6 the size at 50KHz. The filter components would follow the same scaling except that stagger firing will not be employed. For that reason, the larger numbers would be used in scaling the filter sizes. Table 7-10 shows this dependent component size vs. frequency of operation for a 10KW and 20KW system using 1KW modules.

Table 7-10

	f_o (KHz)	Component Size at f_o (in^3) min	max	Number of Components at 10KW	Size at 10KW (in^3) min	max	Number of Components at 20KW	Size at 20KW (in^3) min	max
Transformer	10	37.5	50	10	375	500	20	750	1000
Filter	10	25	37.5	10	250	375	20	500	750
TOTAL	10				635	875		1250	1750
Transformer	25	15	20	10	150	200	20	300	400
Filter	25	10	15	10	100	150	20	200	300
TOTAL	25				250	350		500	700
Transformer	50	9	12	10	90	120	20	180	240
Filter	50	6	9	10	60	90	20	120	180
TOTAL	50				150	210		300	420

7.5.3.3.4 Size Summary

The space factor can again be assumed to be .8 and 1.5. Summing Tables 7-9 and 7-10 will yield the size Summary Table 7-11 below.

Table 7-11

Size Summary Table for 1KW Modules System at 10KW and 20KW

	f_o	Total Volume at 10KW min.	max.	Total Volume at 20KW min.	max.
Component size(in^3)	10	753	1000	1398	2025
Wiring space(in^3)	10	451	1500	839	3038
TOTAL size (in^3)	10	1204	2500	2237	5063
Component size(in^3)	25	368	575	648	975
Wiring space(in^3)	25	221	863	389	1463
TOTAL size (in^3)	25	589	1438	1037	2438
Component size(in^3)	50	268	438	449	685
Wiring space(in^3)	50	160	653	269	1028
TOTAL size (in^3)	50	428	1091	718	1713

As can be seen from the above, a conditioner operating from 10KHz to 100KHz and 10KW may be as small as 1204 in^3 or as large as 2500 in^3. Increasing the minimum operating frequency (f_o) decreases the size considerably. However, as one reduces the size of each component or module, the overall packing factor will decrease with a resulting increase in lost space. Therefore, the estimates for 25KHz and 50KHz conditioners should be taken from the middle and high ends of the spread of Table 7-11 respectively.

7.5.4 Induction Positioner Supply Size and Weight

The estimates of the previous two sections can be used to estimate the size and weight of this supply. A conservative estimate of weight would come from Table 7-5 at 4.5 lbs. (excluding tank circuit transmission line and coil). The size estimate would come from Table 7-7a.

Table 7-12.

Component	Size (in^3)
Transistors	1
Transformer	3
Base Drive	2
Logic	44
Filter	10
Wiring Space	60
TOTAL SIZE	120

Therefore, the positioner may be 120 in^3 and 4.5 lbs if conventional approaches to wiring and packaging are used.

7.6 SUMMARY

A technique has been proposed for both the electron beam and induction supplies whereby both the regulation and inversion are accomplished with one set of power switching devices. This technique should raise the overall efficiency above that of a preregulated supply. The overall efficiency has also been shown to be a function of the acceptable weight and size constraints. An increase of 20% in weight may be necessary to increase the operating efficiency from 85% to 90%. This increased weight will primarily be due to an increase in the size of the magnetic components to allow more efficient transformation.

The proposed modular approach has been employed in the past and has been shown to be reliable because of the reduced component stresses. The ultimate in performance of this approach will be when each module is fabricated in hybrid form so that the entire conditioner can be fabricated in a compact form without the resulting mass of wiring attendant to conventional wiring schemes.

The utilization of small modules and transistor switches with low conduction voltages will bypass the problems of efficiency attendant with the low input voltage of 25.5V. In fact, the low input voltage increases the number of devices which would be suitable for such a design. Therefore, it is not deemed necessary to series the supply to arrive at an efficient system.

If the power conditioners are constructed of ten 1KW modules then the summary of Table 7-13 below is valid for the electron beam supply and the induction coil driver at 25KHz.

Table 7-13

Power Conditioner Summary at 28V Input

Supply	Transistor Parameters V_{CE}	I_C	Weight (lbs/KW)		Size (in^3/KW)		Efficiency (%)
Electron Beam	100	44	6	7.5	67	162	90
Induction Coil	100	55	5.3	7.3	59	144	88

It can be seen that high efficiency is possible in both cases. Also, the induction supply will be inherently less efficient due to increased losses in the power devices due to the higher conduction losses of the transistors operating in a non-square wave mode.

Previous work at the R&D Center has shown that the high voltage rectifier technology exists in the industry to provide devices for this application. Unitrode has proven themselves to be leaders in area of high voltage, high frequency controlled avalanche devices.

The self regulated inverter design has been fabricated in the Schenectady laboratory at a power level of 800W when related to this project. The problems attendant with core saturation due to unsymmetrical circuit operation have been solved in this application. Other specific techniques are also available to the circuit designer.

The number and size of the modules chosen in this multi-cylinder approach will depend on the system constraints and available transistors.

When the volume and weight data of this section is applied to the electrical equipment for the three process examples discussed in detail in Section 5, Table 7-14 results. It should be noted that the volume and weight estimates for the H. F. generator used for the zirconia experiment were obtained from consideration of commercially available H. F. communications gear exclusive of power conditioning. Specifically, data on the Collins Linear Power Amplifier No. 548U was scaled to the higher power level considered here.

It should be noted that the high component densities indicated in this section and summarized in Table 7-14 appear appropriate for an unmanned automated facility such as the shuttle pallet where in-flight maintainability is not a consideration. Such high density of packaging may not be desirable for a dedicated Space Laboratory payload. Since the modular approach recommended here would allow for rapid in-flight maintenance (e. g., replacement of a defective power module), it may be appropriate to use a somewhat lower packaging density to facilitate diagnosis and replacement of individual electronic modules.

A further reservation should be expressed regarding the required total powers estimated in this report and summarized in Table 7-14. The heating efficiencies are in some cases based on very preliminary engineering estimates and further work is required to refine these numbers. This is particularly true when utilizing R. F. induction heating for good conductors such as the case for the beryllium experiment. For good conductors, the induction heating efficiency is relatively low so that power losses in tank circuit and transmission line become relatively important. Achieving the efficiencies assumed as a basis of this work will require the use of very low loss transformer core materials, the use of well annealed oxygen free copper in transmission lines and coils and careful engineering design. These losses are relatively less important in the case of high resistivity materials such as zirconia and in cases where electron beam heating is used such as the tungsten example.

Table 7-14

WEIGHT AND VOLUME OF R. F. GENERATORS
AND POWER CONDITIONING EQUIPMENT

EXPERIMENT	Total Vol	Total Wt	Power Oscillator		E. B. Power Conditioner		R. F. Power Conditioner		R. F. Power In	R. F. Power Out	E. B. Power In	E. B. Power Out
	M^3	KG	WT KG	VOL M^3	WT KG	VOL M^3	WT KG	VOL M^3	KW	KW	KW	KW
TUNGSTEN	.042	49.5	4.5	.002	45	.04	--	--	.100	.060	14	10
BERYLLIUM	.09	98	98	.09	--	--	--	--	20	11	--	--
ZIRCONIA	.50*	135*	70	.04	--	--	65	.05	20	10	--	--

*Estimate