same conditions as the all-brass configuration. The variation in temperature as a function of nozzle gap for both the brass and vacuum jacketed configurations is shown in Fig. 4. Ignition was achieved with the vacuum-jacketed configuration at a nozzle gap of $\frac{19}{64}$ in. The ignition and resulting combustion resulted in the melting of the vacuum jacketed apparatus.

While the results clearly demonstrate the feasibility of the resonance effect as an ignition method, there are several problems which must be solved before actual testing of an igniter in a rocket engine can be attempted.

The apparatus must be constructed of a material with low thermal conductivity to minimize the heat leak so that ignition can be obtained as well as a material which can withstand the intense heat of combustion following ignition. The resonance igniter must be able to operate over a range of ambient pressures and with propellant mixtures at cryogenic temperatures so as to be usable for engine restarts in space. The effects of the other variables must be studied to determine the optimum igniter configuration.

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Storage of Human Organs for Transplantation

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A METHOD for indefinite preservation of organs is critically needed. Such a method, when found, will permit establishment of organ banks. The limited supply of healthy organs from cadavers will be efficiently harvested by removal of several organs from each cadaver. Immunologic rejection will be minimized by preoperative tissue testing of the proposed recipient with multiple potential donors for the best compatibility. The timing of operation to fit the need of the recipient, and the use of only a single surgical team will enlarge the number of individuals receiving needed transplants.

Short-Term Storage Techniques

The integrity and function of the cells of the human body are dependent upon complex intracellular chemical reactions. Interruption of this steady state of metabolism, whether by toxins, deprivation of nutrients, or accumulation of waste products results in cellular damage and eventual death. Various ingenious storage techniques have been devised to support cellular metabolism.

Perfusion with blood substitutes, combined with oxygenation and chemical replenishment, is practical for only a few hours. Irreversible swelling (edema) of the organ associated with circulatory stasis supervene. Perfusion by temporary vascular anastomoses to an intermediate host animal technically is feasible. Unfortunately, the immunologic rejection phenomenon prevents prolonged storage. Hypothermia to 0–5°C slows cellular metabolism reversibly for up to 90 min for whole organs. Storage is further prolonged under hyperbaric oxygenation at 3–7 atm combined with hypothermia.

Animal kidney, heart, and intestine have been preserved up to four days using hypothermia and hyperbaric oxygenation supplemented by a slow perfusion. The most impressive clinical results are those using a sophisticated hypothermic perfusion of oxygenated cryoprecipitated human plasma. Human kidneys have been preserved for as long as 32 hr prior to transplantation.[1] None of these techniques permits prolonged oxygen storage without deterioration as required for banking.

Frozen Storage of Cells and Blood

Although recovery of viable cells after freezing was first reported in 1949, commercially profitable processes for frozen storage of spermatozoa and bacteria are now in use. Human red blood cells stored for weeks by freezing, have been used in Viet Nam for transfusions.

Freezing and thawing processes are not innocuous to living cells.[2] Damage is related to the formation of ice crystals, the denaturation of proteins by dehydration, the changes in pH as buffer salts crystallize, the hypertonicity of preservative chemicals and the edema that accompanies cellular damage. Empirically, the use of water-binding substances such as dimethylsulfoxide (DMSO) and glycerol, along with precise temperature control have proven to be protective in certain situations (see Table 1). These chemicals are hypertonic in protective concentration, and are known to cause some degree of cellular damage. If cooling is too slow, if storage temperature is too high, or if heating is not extremely rapid, then the deterioration of tissues is great. Overheating beyond 42°C causes rapid destruction of biological tissues.

Table 1 Protection against freezing injury

Cryoprotective chemical	DMSO (Dimethylsulfoxide) or Glycerol
Rapid freezing	1–10°C/min
Cold storage	−196°C
Rapid thawing	25–100°C/min

Table 2 Ratio of surface area to volume

	(cm^{-1})
Red blood cell	16,000
Skin graft	30
Small intestine	8
Heart	2
Kidney	1
Adult human body	0.2

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Frozen Storage of Skin, Parathyroid Gland, and Intestine

Techniques developed in this laboratory for storage of animal skin have been extended to a human skin bank.[3] Thin grafts of skin were treated with 10% glycerol, frozen at 1–10°C/min, stored in liquid nitrogen at −196°C for up to 19 months, and thawed rapidly for use by immersion in warm saline solution at 25–100°C/min. These grafts provided temporary lifesaving coverage for patients with extensive burn wounds before being rejected immunologically.

The same techniques have been extended successfully to the storage of canine parathyroid glands, tiny glands that control calcium metabolism. These frozen preserved glands can sustain the life of the animal.

Short segments of canine intestine treated in the same fashion have survived freezing in liquid nitrogen for as long as five weeks. The intestinal segments were distended to the shape of a thin walled hollow cylinder. Warm saline solution was introduced on both sides of the intestinal wall for rapid thawing by conduction. The segments required one to two weeks of cellular recovery from freezing injury to resume normal function which included muscular action, secretion of mucus, and absorption of glucose. This success indicated that the several cell types of a single organ would survive a common cryoprotective treatment.[4] Determination of optimal concentrations of cryoprotective agents and satisfactory control of organ edema are problems still to be solved.

Frozen Storage of Solid Organs

Special problems exist in the frozen storage of large solid organs such as kidney, heart, and liver.[5] Heat exchange in the living animal is rapid because of the intimate contact of the circulatory system with all of the cells. Internal temperature gradients are small. In contrast, large thermal gradients develop during heat exchanges in frozen solid organs. These resemble blocks of frozen salt solutions in their thermal properties of low-heat conductivity, high-heat capacity, and large heat of fusion. The low ratio of surface area to volume for solid organs severely limits heat exchange with the surroundings (see Table 2). Satisfactory rates of thaw cannot be achieved by immersion in warm liquids. Perfusion of the blood vessels with gases is a potential means of internal heating, limited by the low rate of heat transfer from the gas to the organ.

Electrical Thawing

Electrical heating, by generating heat within the substance of solid organs, can overcome the problem of poor thermal conductivity. Uniform heating is dependent on the distribution of the electrical field and the local electrical resistance of the tissue. The electrical properties of tissues are similar to those of dilute aqueous salt solutions. The electrical conductivity is a function of temperature over a wide range of frequencies. There is a rapid rise in conductivity increasing with rising temperature when tissue passes from the frozen to the thawed state. Recently, canine kidneys were thawed at 50–100°C/min using a microwave oven operating at 2450 MHz.[6] Although a satisfactory over-all thawing rate of 60–100°C/min was attained, none of the eight kidneys survived after reimplantation. On closer inspection it was obvious that heating was far from uniform. Certain areas of some kidneys overheated, even to the point of burning, while adjacent areas remained cold or frozen.

That microwave thawing is not inherently toxic to cells was established by a comparison of frozen skin grafts thawed by microwave and by thermal conduction techniques. Skin grafts survived after microwave thawing although there was some damage associated with focal overheating.

This phenomenon of uneven thawing during electrical thawing, named thermal runaway, was investigated using a two-dimensional mathematical model and a digital computer.[7] Isotherms were calculated over the period of time required for thawing of the model. The experimentally observed increase in electrical conductivity with increasing temperature was included in the equation of the model. The analysis verified the nonuniform characteristics of the thaw with some areas remaining frozen while others overheated. Important variables were the temperature at the beginning of the electrical thaw, the temperature at the boundary of the organ, and the strength of the applied electrical field during the thaw. Experiments performed using electrical conduction thawing at low frequency verified the conclusions of the mathematical model study.[8]

Conclusions

The need for a human organ bank for transplantation is great. The extrapolation of techniques proven successful in the frozen storage of cells has proved extraordinarily difficult for large solid organs. The constraints imposed by the properties of biological tissue render the control of heat exchange very difficult. It is hoped that proper application of engineering principles within these specific limitations of biological tissues will permit satisfactory rates of heat exchange. Further refinement of cryoprotective perfusion techniques are needed. Better methods of suppressing edema are urgently needed. The fact that certain organs have survived freezing makes the creation of a frozen organ bank for transplantation a likely event.

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Calculation of Maximum Velocity Decay in Wall Jets

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Nomenclature

b = outer boundary-layer thickness
C = constant
D = nozzle diameter
K = δ/b

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