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NUCLEAR PROPULSION TECHNOLOGY TRANSFER TO ENERGY SYSTEMS*

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Abstract

At Los Alamos, space technology has been applied to terrestrial energy problems. Four examples illustrate this transfer process: (1) heat pipe technology developed for space power supply systems cooling is being adapted to the methanation of synthetic natural gas from coal, (2) high temperature materials from the Rover nuclear engines are being adapted to an excavation concept based on melting rocks or soils, (3) high temperature graphite fuel technology is being applied to high temperature gas cooled reactors and, (4) cryogenic hydrogen and helium technology is being applied to superconducting electric power transmission and storage systems. An overview description of the above projects is presented in the hopes of stimulating thinking with regard to the transfer of space technology to terrestrial energy problems.

I. Introduction

In recent years there have been numerous instances where organizations deeply involved in space propulsion and allied fields have been faced with program cutbacks and cancellations and the subsequent problem of how best to utilize the skills and technologies available to the affected organization. Such a situation prevailed in recent years in one segment of the Los Alamos Scientific Laboratory (LASL) where the Rover Nuclear Rocket Program was cancelled after about seventeen years of extensive study, design, fabrication, and testing of liquid hydrogen-cooled, high-temperature, nuclear-powered space rockets. Subsequently, the "Q (Energy) Division" was organized with its efforts devoted primarily to terrestrial energy problems. An overview is presented in this paper of four terrestrial energy problem areas which are being worked on by the new LASL division. The objectives of this paper are to inform and to, perhaps, stimulate new ideas for applying space technology to terrestrial energy problems.

II. Descriptions of LASL Energy Projects

Heat Pipes Applied to Methanation of Synthetic Gas Derived from Coal

Heat Pipes

Heat pipes were developed at LASL for satellite and space power supply systems and are now being investigated to solve a synthetic gas methanation problem as will be described below.

The capillary pumping feature of the heat pipe makes it particularly attractive as a method for solving many problems in heat transfer, isothermalization and temperature regulation. Other interesting heat pipe features include the self-contained nature of the device, its relative simplicity and its ability to transport large amounts of heat with very small temperature drops. Figure 1 shows a cutaway section of a typical heat pipe design where liquid pumping is done entirely by capillary forces. In the figure, heat is shown being introduced at the top of the unit, causing the working fluid to evaporate. The vapor flows to the heat removal region (shown at the bottom of the pipe) where it is condensed, giving up its latent heat of evaporation in the process. The liquid condensate is then pumped back to the top of the unit by capillary forces in a high porosity wicking material that lines the inner wall of the device.

The Problems of Methanation

Virtually all processes for making synthetic natural gas from coal include a step for upgrading the raw product gas to a high Btu pipeline quality gas. This is done by using the so-called shift reaction to increase the molecular hydrogen-carbon monoxide ratio in the raw gas to a range of 3.0 to 3.1, then passing this mixture through a catalyst bed where it reacts exothermally to give a nominal yield of $CH_4 + H_2O$.

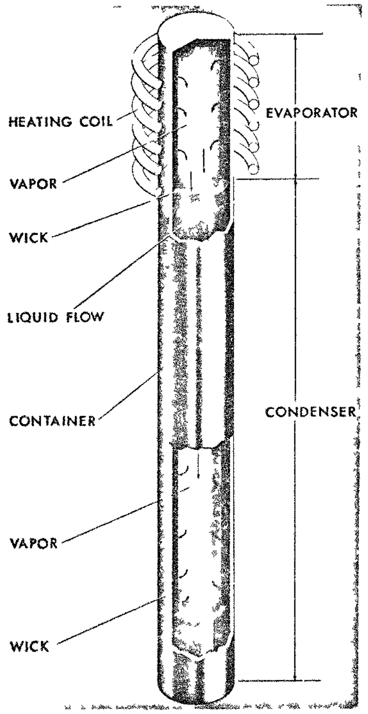

Fig. 1. Elements of a heat pipe.

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A major problem in the design of units to carry out this methanation reaction is the removal of heat from the catalyst bed. If the catalyst temperature is not held within relatively narrow limits, the poisoning rate tends to rise sharply and catalyst lifetime is markedly reduced. An even more serious consequence of inadequate heat removal is the formation of hot spots, which can propagate and rapidly destroy the effectiveness of the catalyst bed.

Methods currently being developed for methanator catalyst cooling fall into two categories. In the first of these, the hot-gas recycle scheme, the heat capacity of the reacting mixture is used to remove the reaction heat.[1] This requires that 90% or more of the gas passing through the catalyst bed be diverted through a heat exchanger to reduce its temperature and then recirculated through the bed. Advances in catalyst bed design have reduced the pumping costs associated with this recycle operation to an acceptable level, but catalyst effectiveness, measured in terms of the volume of methane produced from a unit mass of catalyst before the latter needs to be replaced, has been low. This is probably a result of the ~ 100 K temperature rise that occurs between the entrance and exit of this type of methanator unit despite the recycle cooling procedure. This rise prevents operation of the catalyst bed at a uniform optimum reaction temperature.

The other general type of cooling scheme used for catalyst cooling is to bring the catalyst into contact with a metal wall that is cooled by boiling Dowtherm A heat transfer fluid. One method of achieving this is to use the reacting gas mixture to fluidize a bed of small catalyst particles in a tube whose walls are cooled with Dowtherm A. Another is to place catalyst pellets in an array of tubes that pass through a vat of Dowtherm A. The reacting gas mixture flows through these tubes and convectively transfers the heat from the pellets to the tube walls. Adequate temperature control with this method requires small tube diameters and hence an exceptionally large number of tubes is needed for a methanator of this design.

The greatest success obtained to date, from a standpoint of catalyst effectiveness, has been with a scheme whereby the catalyst is flame-sprayed onto the outer wall of a reentrant tube assembly through which Dowtherm A is passed. In this design, called the Tube Wall Reactor,[2-4] the Dowtherm A flows down the inner of two concentric tubes under a gravity head. It then passes up through the annulus between the two tubes and is vaporized by the reaction heat. The vapor from a large number of these tubes travels to a plenum and then to a heat exchanger unit, where it is condensed and led into the gravity-feed tank. The high degree of catalyst effectiveness obtained in tests of single reentrant tube assemblies is believed to be a result of the temperature uniformity obtained with this method of catalyst cooling. However, the need to replace catalyst every six months requires that each unit of the multi-tube array required for the methanator be removable. This means that the tubes must be mounted with large flanges capable of withstanding pressures of ~ 6.9 MPa (1000 psi) and temperatures of ~ 675 K (756°F). Lack of header space further complicates the design problem and the result has been the abandonment of this design in favor of a simpler configuration where the catalyst is applied to the inner wall of the tube in a design otherwise similar to the pellet design described above. This has made catalyst application a slow and difficult process and initial test results with inner-wall coated tubes have been disappointing.

The Heat Pipe Methanator Concept

Because of the difficulties associated with the above methanator designs, an attempt was made to apply the special capabilities of the heat pipe to the solution of the heat removal problem. This has led to a heat pipe methanator design[5] that has the following features: (1) simple configuration combining catalyst bed, incoming gas preheat section, and thermal recovery, (2) easy replaceability of catalyst, (3) short downtime for catalyst replacement, (4) lack of requirement for a multiplicity of large, leak-prone, high-pressure seals, (5) redundancy of operation, and (6) low inventory of heat transfer fluid.

A schematic representation of the Heat Pipe Methanator (HPM) is shown in Fig. 2. It consists of an array of gravity-return heat pipes enclosed in a manner that provides for methanation with (1) low temperature drop (ΔT) catalyst cooling, (2) preheating of the inlet gas stream, and (3) recovery of the reaction heat by a steam-generating heat exchanger, all in a single unit. The heat pipes are supported by a grid plate at the right-hand side of the unit. At the other end of the methanator chamber, the heat pipes are slip-fit into a multithimble configuration, which provides the heat transfer surface for the thermal recovery heat exchanger. The latter is a separate chamber at the left-hand side of the unit. Flow baffles are placed in both chambers to establish either a uniform flow distribution or a multipass cross flow configuration.

In the methanation side of the unit, incoming gas passes through the preheat section reaching a temperature of about 650 K (~ 700°F) at which the methanation reaction will take place at the desired rate. At this point it passes into the methanating section. The main difference between the two sections is that in the preheat section the heat pipes are roughened to facilitate heat transfer, and in the methanation section they are coated with a catalyst (probably, but not necessarily, by flame spraying).

In operation, heat is generated by the methanation reaction along the catalyst-coated section of

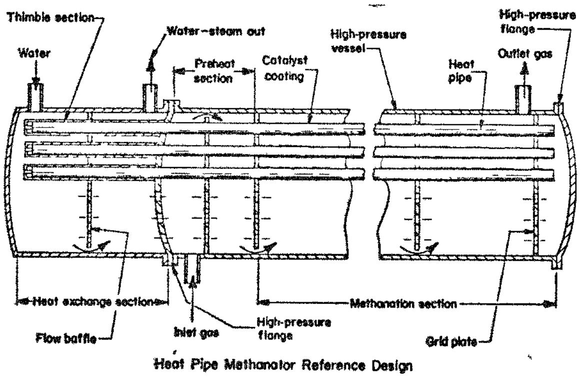
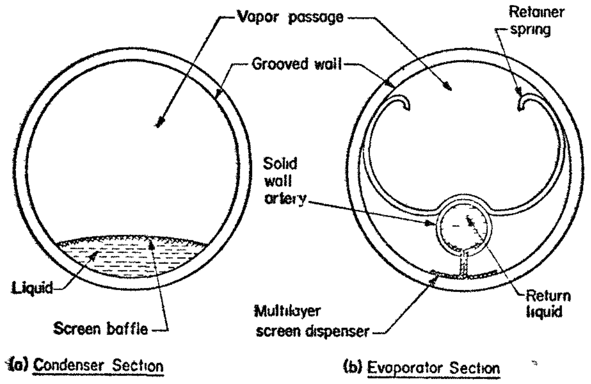


Fig. 2. Schematic showing methanator, preheater, and steam generator in one unit. The heat exchanger would be tilted several degrees above horizontal to enhance gravity return of the heat pipe working fluid.

the heat pipes. This section represents approximately two-thirds of the total heat pipe length because heat input is limited to about 13 kW/m^2 by the reaction rate. The reaction heat vaporizes the working fluid of the heat pipes and is transmitted by vapor flow toward the heat exchanger. Approximately one-fourth of the total heat is deposited by vapor condensation in the preheat section, bringing the incoming gas up to temperature, and the remainder is delivered to the heat exchanger. In each heat pipe the condensed vapor is returned by gravity flow in a baffled flow channel to the catalyst-coated section of the pipe. Heat transfer in the heat exchanger occurs by conduction through the annular gas gaps between the heat pipes and the thimble walls. The sizing of this gap depends on the temperature desired in the heat exchanger, as well as the steady-state composition of the gas mixture in the gap and the length of the heat exchanger thimbles. It will probably be in the 0.1- to 0.2-mm range so that replacement of the heat pipes should not be difficult.

The dimensions of the methanator unit will depend on system cost-effectiveness considerations but the following estimates represent a reasonable point of departure. An individual methanator unit might consist of a pressure vessel about 1.2 m in diameter and just over 11 m in length, containing 500 heat pipes 51 mm in diameter in a hexagonal array having a 60-mm pitch. The heat pipe length will be approximately 11 m, 8 m of which are catalyst coated. Such a unit would have a total catalyst surface area of about 650 m^2. Current values for the 3 H_2 + CO reaction rate are 3.6×10^{-3} $m^3/s/m^2$ of catalyst surface area at a pressure of 6.89 MPa (1000 psi) and a reaction temperature of 670 K. Thus, this size methanator would produce 2.3 m^3/s of methane or 7.1×10^6 ft^3/day. Therefore, a 250×10^6 ft^3/day methanation plant would require 35 methanator units.

The use of gravity to assist liquid return necessitates modifications of the simple wick design shown in Fig. 1. Chief among these is the incorporation of low flow-resistance channels for liquid return. The liquid in these channels must be protected from interaction with rapidly moving vapor flowing in the opposite direction because this interaction can markedly reduce heat pipe performance. How this protection is accomplished in the reference design for the heat pipe methanator is shown in Fig. 3. In the condenser section (Fig. 3a), vapor condensing on the tube wall flows to the bottom of the tube and proceeds along the bottom by what is termed "puddle flow" to a transition region where it is diverted into the pedestal artery configuration shown in Fig. 3b. A screen baffle is placed at the bottom of the tube in the condenser section to reduce the vapor-liquid counterflow interaction and yet not interfere with the circumferential flow of condensed liquid to the bottom of the tube. The puddle flow at the bottom of the tube somewhat reduces the effective heat transfer area, but this is offset by the simplicity of the configuration.



(a) Condenser Section (b) Evaporator Section

Liquid Return Flow Channel Design

Fig. 3. Cross-sectional views of the reference design methanator heat pipe.

The artery in the evaporator section of the heat pipe is a solid wall tube with a slot in the bottom where several layers of fine mesh screen are crimped. The tube wall shields the liquid returning from the condenser from direct interaction with the oppositely moving vapor stream. The screen serves to dispense the returning liquid to the evaporator tube wall capillary structure and also helps to minimize heat flow from the tube wall to the artery. Some degree of thermal isolation of the liquid in the artery is required to restrict the formation of vapor in the artery and prevent appreciable vapor flow up the artery with its consequent restrictive effect on the return liquid flow.

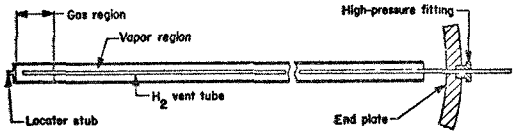
Capillary flow is used to distribute the working fluid to the entire inner surface of the evaporator. This is accomplished either by machining fine circumferential grooves into the interior wall of the heat pipe or by lining this wall with one or two layers of screen.

Heat pipes can be constructed to operate over the wide temperature range from a few degrees K to 2500 K. However, for temperatures in the vicinity of 675 K required for the methanator application, selecting a suitable working fluid is difficult. Mercury, sulfur, high temperature organic fluids such as Dowtherm A and even cesium and potassium are potential candidates. The final selection will depend on consideration of cost, toxicity, heat transfer capability, thermal stability and chemical compatibility with wick and wall materials.

Temperature control of the heat pipe is achieved by adding inert gas and by providing a region at the condenser end where the heat deposition rate increases rapidly with axial distance. In operation, the working fluid vapor pumps the inert gas to the condenser end of the heat pipe where a vapor-inert gas interface is established. The volume occupied by the inert gas decreases or increases as the input heat increases or decreases, respectively (with more or less heat transfer area being required to dump the heat transmitted to the heat exchanger). Volume changes result in inverse changes of pressure, establishing the vapor pressure of the working fluid and therefore its operating temperature. Because the vapor pressure of the fluid generally increases rapidly with temperature, relatively large pressure variations can occur without causing undue changes in operating temperature. The temperature can be varied by changing the quantity of inert gas added to the heat pipe. The desired heat removal profile for establishing temperature control can be obtained by varying the heat pipe to thimble wall gap thickness.

Hydrogen diffusion into the heat pipe is the major problem to be overcome in the development of an economical heat pipe methanator. The effect of this diffusion is to increase the gas pressure inside the heat pipe and hence increase the operating temperature of the device. Potential methods of controlling hydrogen influx include the introduction of a low permeability barrier layer, such as aluminum, into the wall of the device and the use of hydrogen-getter materials, such as zirconium. Should such control measures result in excessive cost of the heat pipes, a third option, that of continuous venting, is available as a backup measure.

The manner in which continuous venting can be achieved is shown in Fig. 4. Small diameter tubes are welded into each pipe, extending from the right-hand end of the heat pipes to the inert gas region at the other end. Excess gas accumulating in the inert gas section of each heat pipe is bled off through the vent tubes to a common pressure regulating system. Because the gas overpressure determines the heat pipe operating temperature, a system of this type enables the latter to be continuously monitored and changed, if desired. Barring interconnection of the heat vent tubes inside the high pressure vessel, the continuous venting design requires a separate high pressure fitting for each heat pipe. However, in contrast with the initial version of the tube wall reactor, these fittings can be very small so that leakage is less likely to occur and space is not a problem. These considerations, coupled with the ease of access for detecting and repairing any leaks which might occur, make continuous venting a viable option, though not the first choice, for the heat pipe methanator design.



Continuous Venting Heat Pipe Design

Fig. 4. Heat pipe design option for continuous venting operation.

High Temperature Materials Applied to Excavation

Historical Background

Some components of the LASL Rover nuclear rocket engine operated at temperatures up to ~ 2800 K. While working with these high temperature materials, LASL scientists realized that they were working above the melting points of most rocks and small scale laboratory tests soon demonstrated that small electrically heated "rock drills" were feasible. The idea lay relatively dormant until 1971 when a LASL study of many applications for rock melting devices was published,^{6} including concepts for large nuclear powered tunneling machines, and the name "Subterrene" was applied to the broad family of possible rock melting excavation devices. Since then, research funding has been available from both the Atomic Energy Commission and the National Science Foundation, reference 7 being the most recent program status report.

Subterrene Concept Description

The Subterrene is a system for making vertical or horizontal holes in rocks and soils by progressive local melting. Most rocks, including many very hard rocks which are particularly difficult to penetrate mechanically, melt at temperatures far below the melting points of refractory metals such as molybdenum and tungsten. The rock melt produced can be chilled to a glass and formed into a dense strong firmly attached hole lining that is clearly discernable in the sample shown in Fig. 5. Thus, by the use of a melting penetrator, permanently self-supporting holes can be made even in unconsolidated sediments. The energy utilized to form a hole of a particular size and line it with rock glass is estimated to be greater for a Subterrene than for a conventional rotary drill, but this should be more than balanced by savings in material, labor, and operating costs.

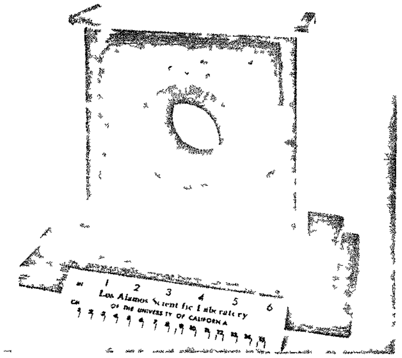


Fig. 5. Cross-section of hole melted in tuff by a consolidating type Subterrene penetrator.

The penetrator, which plays the role of the drill bit, is nonrotating and made of a refractory metal and heated electrically by means of a pyrographite resistance-heating element. Thermal energy is transferred from the heater to a graphite thermal receptor by radiation and is then distributed throughout the penetrator by conduction. The heated portion of the device is thermally insulated from the stem advancing section by a layer of a special pyrolytic graphite. For very large devices the use of a nuclear energy source can be considered.

In operation the hot penetrator is forced into the ground by exerting a downward thrust on the stem. The surrounding rock is melted and the thrusted penetrator forces the liquid rock-melt outward around the penetrator and stem where it is cooled. The melt then freezes to form a hard, obsidian-like glass lining on the wall of the hole, sealing and supporting it. The operation just described is that of the "melting-consolidating" type of Subterrene penetrator designed especially for making holes in porous rock or soft ground. Because the glass-lining formed when the rock-melt solidifies is more dense, and hence occupies a smaller volume than did the original porous rock, the molten debris from the hole can be entirely consolidated in the dense glass lining thus completely eliminating the debris removal operation necessary in conventional drilling techniques.

Holes in dense rock are produced with an extruding Subterrene which can also be used in porous rocks to make holes with a thinner glass lining. The essential structural difference from the melting-consolidating design is that the heated penetrator is not a solid conical body but has the form of a ring or torus with a small hole in the center as shown in Fig. 6. Part of the rock-melt is forced upward and upon cooling forms the hard glass-like lining of the hole. Most of the melt, however, is

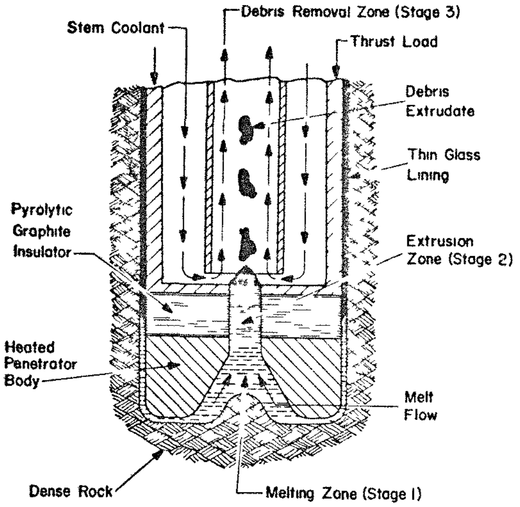


Fig. 6. *Schematic of extruding Subterrene penetrator concept.*

forced up through the central hole in the penetrator into what is called the "extrusion zone". In the upper part of this zone the melt is cooled and solidified; the extruded solid debris, shown in Fig. 7, is then carried to the surface by the cooling gas flow.

With the Subterrene concept the three major facets of excavation, namely, rock fracturing, debris removal, and wall stabilization, are achieved in a single integrated operation. In loose or porous formations the debris removal operation is eliminated by density consolidation. Another unique advantage of the Subterrene system concept is that the holes are automatically lined with a hard glass-like material. It may thus be possible to eliminate the costly and time-consuming procedure of inserting and cementing metal casings typically associated with wells drilled with rotary bits. In tunnels, the rock-glass liner provides continuous wall stabilization during the excavation operation as well as contributing to the permanent structural support.

Applications of the Subterrene Concept

Improved techniques for making vertical or horizontal holes in the earth can have profound effects on our quality of life and directly or indirectly affect terrestrial energy systems. First, let us look at the magnitude of the overall excavation requirements in the United States. The urgent needs for new and innovative improvements in underground excavation were described in 1968 in a National Academy of Science report[8] which showed that environmental, monetary and other benefits could be significant. More recent estimates[9] are similarly impressive. These data show a \$240 billion requirement for all excavation in the U.S. during the next ten years. Included in this figure was \$14 billion for transportation tunnels to 1980 and a similar amount for water and sewer tunnels to 1980. Excavations having direct impacts on our national energy posture include mining for coal, uranium, or oil shale; drilling for oil or gas; drilling for geothermal energy in conventional water reservoirs, magma chambers, very deep hot rock, or in geopressurized reservoirs. Also, the use of superconducting electric power transmission lines, which will be discussed later, would require many kilometers of horizontal underground emplacements.

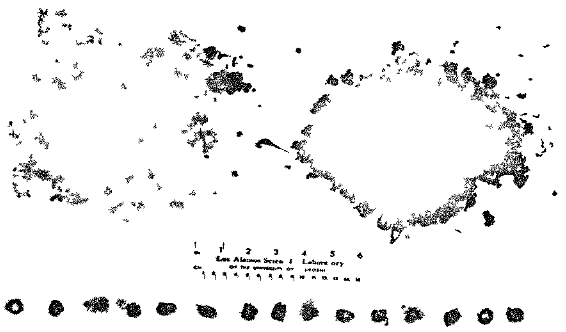


Fig. 7. *Debris from basalt hole made by extruding Subterrene penetrator showing rock wool and glass pellet constituents.*

Studies made at Los Alamos, combined with a survey of potential users in industry, have revealed a large number of potential applications of Subterrene. The inherent ability to make holes of precise diameter and gage could be utilized in producing holes for anchoring structures such as bridges, TV towers, and transmission line towers. Emplacement holes for anchoring pipeline supports could be readily melted in difficult materials such as Alaskan permafrost. The latter capability was demonstrated in simulated permafrost containing ~ 18% by weight of water. Many new small tunnels, especially in urban areas, are needed for utility lines.

LASL has recently studied the problems and needs in the geothermal energy industry.[10] Conventional geothermal reservoirs are typically 2 or 3 km deep with downhole steam or water temperatures of 470 to 660 K. Current rotary drills are capable of drilling into these reservoirs except that the combinations of difficult strata, high temperatures, rotary shocks and torques, and corrosion result in high average well costs. The Subterrene rock melting devices are uniquely suited to operation in hot rocks. Indeed, a recent LASL laboratory test showed enhanced performance while penetrating a block of basalt at a 625 K rock temperature. Subterrenes may be especially useful in the completion zone of a hot well. Another well application would be to use the rock glass liner capability to facilitate drilling locally through troublesome fractured and lost circulation zones.

LASL is now experimenting with the concept of drilling into deep hot granite zones, fracturing the rock to greatly enhance heat transfer surface area and then pumping water through these fractured rocks to absorb the geothermal energy. Such a technique, if successful, would open up a vast new source of energy to the nation. Obviously, the rock melting Subterrene has the potential for producing the deep hot boreholes necessary to maximize the exploitation of the above type of geothermal energy system.

Studies have been made of large tunnels, i.e., 4 to 12 m diam, such as might be used for water or transportation purposes. Reference 11 surveys the current status of the tunneling industry. Reference 12 presents design concepts and an economic analysis of nuclear powered Subterrene tunneling machines. The conclusion was reached that the Subterrene concept may be especially useful in very difficult ground conditions such as loose caving ground or in very hard rocks.

Application Demonstrations Already Accomplished

Laboratory tests have been made in many types of rocks and at penetrator diameters up to 114 mm. The first practical application occurred in early 1973 when eight drainage holes were made for the National Park Service in Bandelier National Monument. Subterrene devices (50 mm diam) were operated on a small portable rig in very fragile kiva areas of ancient Indian ruins where the vibrations of rotary drills could not be tolerated. In order to demonstrate the beneficial effects of the glass lining on tunnel walls, a 1 m wide, 2 m high, and 2 m long tunnel was made. A vertical borehole demonstration is shown underway in Fig. 8 using a recently activated field rig to make a 30 m deep hole in solid basalt.

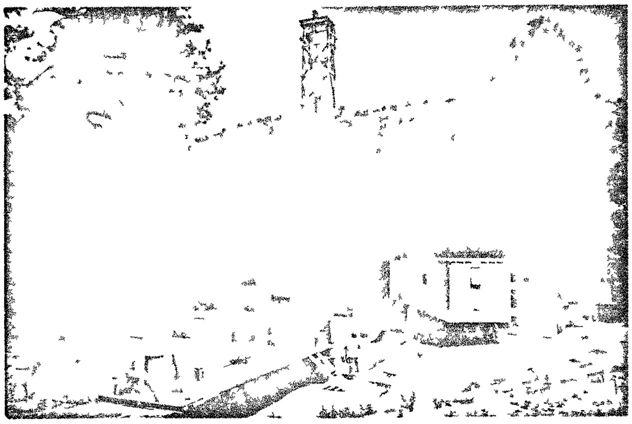


Fig. 8. Subterrene field rig being used to make a 30 m deep borehole, 84-mm-diam, in solid basalt.

Nuclear Propulsion Fuel Technology Applied to High Temperature Gas Cooled Reactors

Potential for Achieving High Temperatures

High temperature graphite reactor fuel element technology based on the LASL nuclear rocket propulsion program is being applied in LASL studies to the high temperature gas cooled reactor (HTGR). Increase in outlet gas temperature into the range of 1200 to 1600°K are possible by incorporating coated fuel particles into extruded fuel elements - a technique developed for propulsion reactors. Potential applications are hydrogen production from coal, hydrogen production in thermochemical cycles, and electric power generation using the direct gas cycle. Current studies include (a) identification of processes for which nuclear heat is needed; (b) systems analysis including engineering, economics, utilization of natural resources, practicality of implementation including the evolutionary and long-term stages, and public and commercial acceptability including environmental concerns; (c) HTGR design and nuclear fuel cycles; and (d) development of experimental processes and materials engineering data for processes using nuclear heat. To the aerospace industry, the development of more economic production costs for hydrogen is of special interest because such a development could lead to a switch from fossil fuels to hydrogen fuels in large aircraft.

The first generation of high temperature gas cooled reactors were designed to produce thermal energy to power a steam Rankine cycle. Optimization of the design for this application led to large differences between the maximum fuel temperature and the exit gas temperature. This is chiefly because the fuel is capable of very high temperature (1700°K) and the exit gas temperature required is very modest (840°K). Therefore large temperature differences which led to design simplifications and economic advantages could be tolerated. By making design modifications to reduce these temperature differences, large increases in exit gas temperature could be attained without increasing fuel temperature.

The nuclear rocket propulsion reactors, developed in the Rover program, were designed and operated to heat hydrogen to temperatures up to 2600°K for periods up to 10 hours. Another LASL ultrahigh temperature experimental reactor called UHTREX that had been worked on at the same time as Rover, and that was originally conceived as a process-heat source, was designed to heat helium to 1590°K and operated at fuel temperatures in excess of 1920°K for 30 days. Both reactors used the same fuel technology (pyrocarbon-coated UC_2 beads) as the HTGR, but the core geometries were more finely divided than in the HTGR, providing for smaller temperature differences between the fuel and the coolant. The reactor operating temperature can be increased in a number of ways classified according to two types: (1) decrease in the temperature difference between the maximum coated particle fuel temperature and the mean exit gas temperature, and (2) increased maximum coated particle temperature. Gains in the latter category are limited by fission product diffusion into the gas stream and increases greater than 100°K are not foreseen. Increases in the former category, however, are readily made and a variety of modifications are proposed as follows: incorporation of coated particles in the fuel matrix; use of a more finely-divided fuel coolant hole geometry to increase heat transfer coefficients and reduce conduction temperature differences; large increases in the fuel matrix graphite thermal conductivity (to about 50 W/m°K) to reduce conduction temperature differences; and modifications to the core distribution, both radially and axially.

Problem areas which must be solved or eliminated in order to increase the gas exit temperature in the HTGR can be identified as those which: (a) are associated with the transfer of energy from the fuel particle to the coolant stream, (b) limit the lifetime of the coated particle, and (c) are safety related. Item (a) includes the thermal resistance of the fuel stick, the gap between the stick and the moderator, the moderator itself and the gas film in the coolant channel. Item (b) includes lifetime limits imposed on the particle due to core migration (amoeba effect), maximum temperatures that the particle coatings will stand, and the nature of the core and coating materials. Part (c) has to do with the fission product release characteristics of the particle and the mechanical integrity of the coated particles. Since the various factors listed are not mutually independent, it may not be possible to consider them separately from one another.

In spite of the formidable technical problems touched upon in the above paragraphs, there is little doubt that with further fuel-technology development and with a different reactor core design, an HTGR-type reactor could be developed to heat helium to temperatures up to 1367°K. Possibly, helium temperatures as high as 1590°K could be attained.[13]

Use of Higher Temperature Nuclear Energy

Two obvious applications for higher temperature nuclear energy come immediately to mind: (1) the generation of electricity at high thermal efficiencies with direct closed-cycle gas-turbine systems (Brayton cycle), and (2) the production of hydrogen at high efficiencies in a cyclic thermochemical process (e.g., see Ref. 14).

The principal advantages of high thermal efficiency are: (1) less primary fuel consumption, and (2) less waste-heat rejection. Other advantages of the Brayton cycle are reduced corrosion problems (with helium as the working fluid) and the possibility of waste-heat rejection by air-cooling without major reduction in thermal efficiency. In steam power plants, maximum temperatures are restricted to ~ 840 K (1050°F) by corrosion problems, and current environmental concerns force the use of cooling towers for heat rejection, which significantly reduces thermal efficiencies, particularly for light water reactor (LWR) plants. In fact, for most energy use projections, forecasters are assuming lower efficiencies for future electric power generation because of these constraints. Why then has electric power generation by high-temperature nuclear-power-driven gas turbines not been given serious consideration? Very simply, in the past reactor designers have maintained that the turbine technology does not exist and turbine designers have maintained that the reactor technology does not exist. We have already discussed the possibilities for reactor development; let us now discuss the possibilities for turbine development.

Although large high-temperature helium turbines have not been developed, turbine designers have maintained for years that, in general, the development problems are less severe than those for the oxidizing atmosphere in aircraft jet engines. And, recently, jet engines for the supersonic transport have been designed to operate up to 1367 K (2000°F) for cruising and up to 1590 K (2400°F) for takeoff. In Europe, reference designs for 300-MW_e closed-cycle turbine-alternator systems with the turbine inlet at 1273 (1830°F) have existed since 1966,[15] but, in the U.S., a serious proposal for an HTGR-gas turbine power plant[16] has been made only recently.

Several disadvantages of nuclear heat make the direct application to high-temperature processes economically uncertain:

- The environment in most process equipment is corrosive and must be separated from the reactor core by a physical barrier, i.e., a heat exchanger. This implies design constraints on the process equipment and requires that fuel temperatures in the nuclear core be significantly higher than those of the process. Actually, the direct circulation of the reactor coolant through process-heat exchangers may be unacceptable because of safety considerations. If, therefore, an intermediate heat-exchange loop would be required, the nuclear fuel temperatures would be even higher.
- The thermal power requirement of most processes, for economic nuclear reactor sizes, is relatively low, possibly with the exception of large steel-plant complexes. Another exception may be the Gulf General Atomic/Stone and Webster Engineering Corp. coal gasification process.[17] Current "standard" coal-gasification plants, based on a synthetic gas production rate of 250 million standard cubic feet per day, require a thermal load of only ~ 400 MW for the water-gas reaction.
- Most high-temperature process industries include multiple, parallel, process streams (usually three or four). This implies that (very high temperature) multiple coolant loops from the nuclear reactor to process vessels are needed, which is another expensive requirement; and a nuclear reactor shutdown would force the shutdown of an entire plant - an operational constraint that may be unacceptable, certainly undesirable.

However, the production of hydrogen may demand both high temperatures plus very large thermal power capabilities. Although a viable process for producing "thermochemical hydrogen" does not exist, the maximum temperature will be as high as practicable to maximize the efficiency (for the same reason as for electric power generation). Therefore the ultra-high temperature reactor can produce hot helium for either electric power or hydrogen production. For hydrogen production, the plant will be necessarily large,[14] eliminating the size-factor disadvantage for most other process-heat applications. The other disadvantages, related to high-temperature process-heat exchangers, are not mitigated, but at least one will be concerned with only one process, that of the yet-to-be-discovered hydrogen-production process, rather than with the multiplicity of process-heat applications.

Cryogenic Technology Applied to Energy Transmission and Storage Systems

Historical Background

During the 1960's the LASL Low Temperature Physics and Cryoengineering Group, especially the Cryoengineering Section, played a major role in the design, construction and operation of several liquid hydrogen test facilities for the Rover Nuclear Propulsion Program at the USAEC's Nevada Nuclear Reactor Development Station. The largest of these facilities included two dewars, which together had storage capability for ~ 3.8 x 10^3 m^3 (10^6 gal) of liquid hydrogen, and fluid flow apparatus capable of transferring liquid hydrogen at rates as high as 3.8 m^3/s (6 x 10^4 gal/min). Meanwhile, another section of the Group had acquired international recognition for its investigations of the fundamental properties of superconducting metals as well as of the analogous phenomenon of superfluidity in liquid helium. The Group has focused its attention on areas of the energy problem to which it could apply its expertise gained from participation in these earlier programs. Currently, three major efforts are underway in large-scale applications of superconductivity and these will be briefly discussed in the following sections.

Superconducting Power Transmission

The commercial availability of high current density (> 10^6 A/cm^2) superconducting materials combined with the present advanced state of cryogenic technology (largely as a result of space program developments) make superconducting power transmission an attractive alternative solution to the impending transmission crisis facing the electric power industry. This crisis will result from: (1) increasing cost and decreasing availability of rights-of-wasy; (2) centralization of large (10 to 40 GW) generation complexes far from load centers; (3) system instability; (4) environmental contraints of various kinds; (5) increased cost and scarcity of primary fuels; and (6) increased requirements for capital.

As a practical and economic means of minimizing the adverse effects of these situations, especially those requiring the transport of large loads (up to 10 GW) over long distances (> 200 km), the LASL proposes a dc superconducting power transmission line (dc SPTL).[18,19] Such a system would be underground, requiring minimal right-of-way (approximately 10 m wide) and offering minimal visual pollution. Refrigeration stations will be spaced every 15 to 20 km and will require less than 0.2% of the line load for operation. Thus, the dc SPTL would be nearly 100% efficient, suffering no resistive, dielectric, or reactive charging losses.

The largest contributions to capital costs of the dc SPTL are the ac-dc and dc-ac converters, the trenching operations, and the cryogenic envelope. The latter two can be significantly pared by decreasing the total line diameter. Hence the LASL designs for the dc SPTL stress simplicity and smallness of diameter, as illustrated by the cross-sections shown in Fig. 9 for two model lines now under study. Each of these would serve as one of two monopoles carrying ± 100 kV at 50 kA to give 10 GVA.

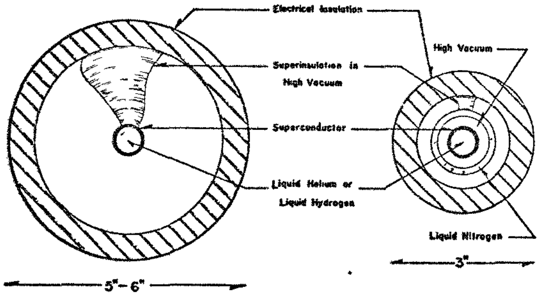


Fig. 9. Schematic cross-sections for two possible small-diameter dc SPTL monopoles, each carrying 50 kA at 100 kV. Note that in each case all metal parts are at the same potential and that the electrical insulation is at ambient temperature. Total heat input is calculated to be 40 W/km.

As LASL's program objective is to optimize the dc SPTL, investigations on different superconducting materials and cable geometries are of paramount importance. These are carried out first in short (< 20 cm) samples and then on specimens up to 20 m long in a test bed. Figure 10 shows two 12 kA leads to this test bed, in which a NbTi conductor (1100 filaments in a copper matrix of 0.25 x 0.50 cm cross-section) has been tested up to 10 kA and at temperatures between 4 and 9 K.

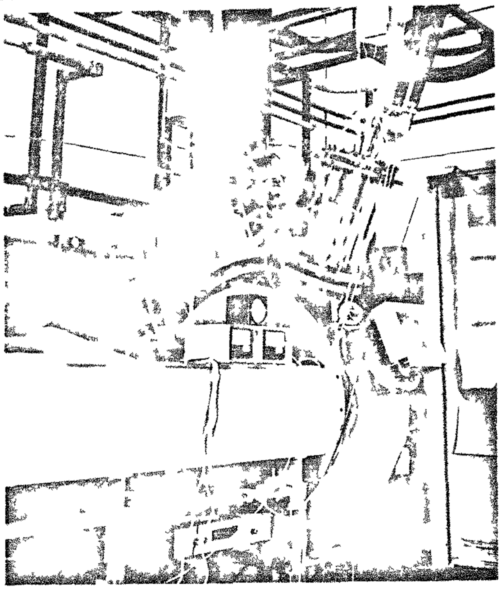


Fig. 10. View of end-drum of 20-m test bed for studying dc superconducting cables. Shown are two 12-kA helium vapor-cooled electrical leads passing from ambient temperature to about 4 K. The cable cryogenic envelope extends to the left, with the conductor making a U-bend in a similar end-drum.

Superconducting Magnetic Energy Storage in the Electric Utility Industry

One of the serious problems faced by the electric utilities results from the daily, weekly, and seasonal fluctuations in demand for power by the consumer. For example, during a given day the peak load may often be more than twice the minimum load, requiring the utility company to use inefficient and costly means to provide the difference. However, by running the generators at some average of the load with the added capability of storing energy during periods of less than average demand to be delivered during periods of more than average demand, up to 35 to 45% less generating capacity would be required for the same total load. This sort of load leveling could result in considerable savings in capital and operating costs as well as conserving fuel.

Of the number of energy storage schemes considered for helping to solve this problem (e.g., pumped hydrostorage, fly wheels, batteries, compressed gas, liquid hydrogen) superconducting magnetic energy storage (SMES) is one of the most promising.[20-22]

A SMES system consists of one or more large magnets - probably of toroidal or solenoidal geometry - which can be charged from and discharged into a transmission line. During the storage phase after charging, a steady dc current circulates through the coil windings; and as these are superconductors, no resistive losses occur. The stored energy density in a magnetic field increases as the square of the current or alternatively as the square of the magnetic field; hence making a storage magnet from superconducting materials capable of supporting very large currents and very high fields allows a SMES-type system to achieve relatively large energy densities, e.g., for a field of 10 T, which can be generated by commercially available superconductors, the energy density is 4 x 10^7 J/m^3, some 80 times larger than that of a hydrostorage system pumped to a height of 50 m.

When it comes to efficiency in transferring energy into and out from the power network, a SMES system has considerable advantage over others. During charge, storage, and discharge, a superconducting magnet should suffer no losses. To effect the energy transfer, a series of electrical "valves" are required which might be in this case, converters and rectifiers (see Fig. 11). Some small losses will be encountered in the valving, but the overall efficiency of the storage and delivery cycle should be 95% or greater. For comparison, pumped hydrostorage units operate with a maximum efficiency of about 70%.

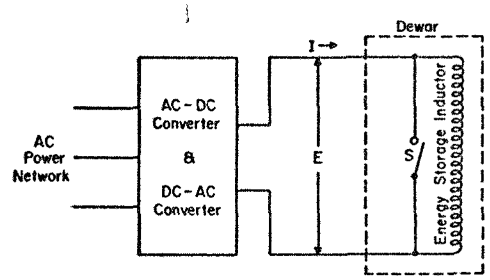


Fig. 11. Schematic of a SMES device interfaced with an ac power network via converters. When switch S is closed, direct current I flows in the inductor circuit without losses (storage mode); S is open during charge or discharge.

Because of the high energy density attainable in SMES systems, energy storage units will be compact and amenable to placement underground or even, in the case of smaller units (of the order 3 x 10^4 MJ capacity), in the basements of buildings (Fig. 12). One particularly attractive model for an electrical network includes SMES units associated with a 5000 MW, 1000 km dc SPTL. To supply such a line with power for 8 hours requires a storage capacity of approximately 10^8 MJ. Rather than incorporating this amount of storage in one unit, which is not practical, we may distribute the storage along the line in 100 10^6 MJ units, with two such units placed every 20 km. This spacing, chosen to coincide with that of the refrigeration units necessary for the transmission line, would be particularly convenient as the refrigeration capacity for initial cooldown of the line is much greater than that needed for steady operation. This excess capacity would then be available for refrigerating the storage units.

The LASL program to develop SMES units is in an early stage. A 1 MJ unit for initial studies is nearly complete and a 100 MJ device is in the planning stage. One of the more difficult problems to be attacked is that of containing the forces generated by the high magnetic fields - an energy density of 1 MJ/m^3 exerts an equivalent pressure of 10^5 kg/m^2 (10 atm). LASL studies indicate that the most economical way of supporting these forces is to transfer them to warm support structures - which may be the surrounding rock - outside the magnet dewar.

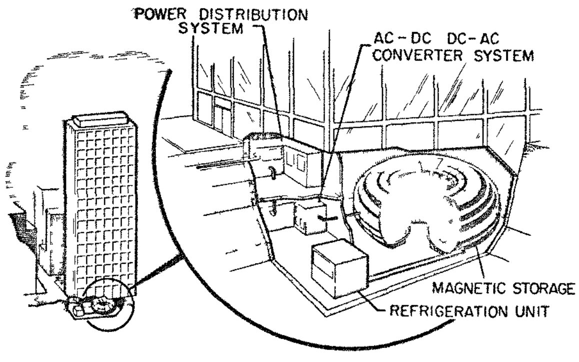


Fig. 12. Artist's conception of a SMES device in the basement of a large building. Storage of 3 x 10^4 MJ would adequately serve the Empire State Building.

Superconducting Magnetic Energy Storage for Thermonuclear Fusion Power

The LASL concept (θ-pinch) for a magnetically confined thermonuclear fusion reactor requires continuously-pulsed, high magnetic field coils to compress the plasma. The demands of various system parameters indicate that magnetic energy transfer and storage (METS) by superconducting inductors is superior to other means - e.g., capacitors - for energizing the plasma compression coils.[23,24] METS, as opposed to SMES, involves a magnet discharge time of the order of 1 to 5 ms, instead of 6 to 8 h; but total storage required will be only about 10^3 to 10^4 MJ. A schematic diagram of a test reactor using METS is given in Fig. 13, where the plasma tube is about 180 m in circumference and the METS system will be required to store about 6 MJ/m.

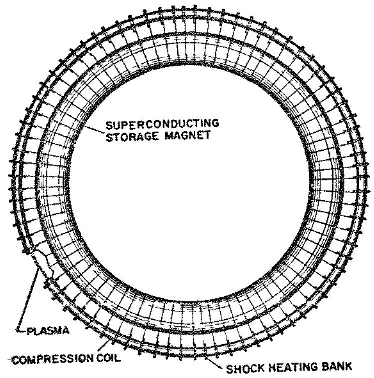


Fig. 13. Schematic of METS system for energizing the plasma compression coils in an experiment to prove scientific feasibility of the LASL θ-pinch fusion reactor concept.

Current LASL work is concerned with testing a 350 kJ coil discharged into an inductive load via a normal-going superconducting switch (maximum efficiency of 25%). Plans are also being devised for 0.6 to 1.2 MJ modules to be used in a reactor experiment and for ambient temperature switching. A problem of considerable concern for a working reactor will be the development of switching methods with an efficiency of 90% or more.

Conclusions

An overview of how one technical organization, the Los Alamos Scientific Laboratory, has applied various facets of space propulsion technology to the problems of national energy needs, has been presented. Energy-related problems being addressed include methanation of synthetic gas derived from coal, earth excavation, nuclear process-heat, and electrical energy transmission, storage, and use in thermonuclear power plants. Technology transfer from space propulsion and space power supply system projects has been demonstrated to be useful in facilitating the initiation of new energy projects. The latter are now rapidly expanding under their own momentum.

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