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Xenon-Filled Silicon Germanium Thermoelectric Generators

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An analysis is presented that shows the desirability and feasibility of using a xenon fill in the initial stages of operation of a silicon-germanium radioisotope thermoelectric generator (RTG) to be used in outer-planetary exploration. The xenon cover gas offers protection against oxidation and against material sublimation, and allows the generator to deliver required power throughout the prelaunch and launch phases. The protective mechanisms afforded by the xenon cover gas and the mechanization of a xenon supply system are also discussed.

Introduction

The spacecraft studied at JPL for outer-planetary exploration is powered by a radioisotope thermoelectric generator (RTG) system of about 450 W at beginning of life (BOL). This is to be supplied by silicon-germanium thermoelectric generators that will eventually be exhausted to the vacuum of space, either by command or through leaks, during transplanetary flight.

During the prelaunch and launch phases, the spacecraft requires approximately 250 W of electrical power. Even if no power were required from the RTGs, the isotope capsules will supply heat that must be removed in a manner that maintains the oxidation-prone materials at acceptable temperatures, or isolates these materials from oxygen. If a high degree of confidence existed that a completely leakproof RTG could be manufactured, the generator could simply be evacuated to 10^{-6} or 10^{-7} torr and vented in space after launch with the knowledge that no oxygen could have entered during the launch and prelaunch phases. In the absence of such confidence it is possible to utilize a generator filled with some inert atmosphere at a pressure higher than atmospheric. This would then produce a sweeping diffusion barrier in any leakage hole, to keep oxygen out of the system. If the right gas were selected, the generators could supply enough power to meet the requirements of the launch and prelaunch phase as well as protect components from degradation.

A number of questions must be answered to understand the use of such a gas:

1. What is the optimum gas to use and why?
2. How does the gas affect RTG operation on the launch pad?
3. How effective might the gas really be in keeping oxygen out?
4. What is there to be gained by keeping inert gas in the RTGs during part of the mission?
5. How is the whole process mechanized?

Gas Selection

For maximum power a gas of low thermal conductivity is required; for minimum gas leakage, low molecular velocities; and for low oxygen back-diffusion, low diffusion coefficients. These requirements are satisfied simultaneously if a gas with a high molecular weight is selected. The most desirable inert gas is obviously xenon, with an average molecular weight of 131.3. Krypton, with a molecular weight of 83.8, is not quite as good; radon is unstable.

Prelaunch Power

It has been shown that xenon, the most desirable gas, allows the RTG to produce more than the 250 W necessary for this phase of the mission. The remainder of this article deals with the last three questions.

Oxygen Flow into a Generator Filled with Xenon

It is highly desirable to exclude oxygen from the RTG during the launch and prelaunch phases. To avoid oxygen inflow, the RTG is to be pressurized at above atmospheric pressure with xenon. This gas will then flow out of any leakage holes. Oxygen can enter the RTG only by a countercurrent diffusion process.

The countercurrent diffusion process depends on leakage hole size and configuration. Since a leakage hole is an unplanned entity, the configuration is quite arbitrary, and a shape must be chosen to enable analysis of the governing factors.

An analysis was made of this countercurrent diffusion process using cylindrical (circular) holes. The process governing the flow of xenon was considered to be either in the free molecular flow regime or in the continuum (nonslip) fully developed laminar flow condition. The countercurrent diffusion of oxygen was then analyzed, and it was found possible to obtain solutions quite similar to the Matricon exponential equation governing diffusion pump operation.

The analytical development is quite straightforward but rather lengthy, and is fully described in Reference 1. The results can be explained with the following set of figures, which apply to an RTG pressurized with 2 atm of xenon surrounded by 1 atm of air and with leakage holes of various diameters and 5-mm length.

Figure 1 shows the outflow of xenon from the generator as a function of hole diameter. Figure 2 shows the inflow of oxygen that would be obtained if the generator were evacuated, also as a function of diameter. Figure 3 shows the "sweep factor," i.e., the factor by which flow values of Figure 2 have to be reduced by virtue of having a countercurrent diffusion rather than an unimpeded flow situation. In the viscous flow regime the sweeping of the oxygen by the xenon is exceedingly effective; in the free molecular flow regime it is — quite expectably — not. Figure 4 shows a leakage hole spectrum that was postulated quite arbitrarily. Figure 5 shows the resultant xenon leakage, a combination of Figures 1 and 4. The integrated value of leakage resulting from the postulated hole spectrum is approximately equal to preliminary leakage specifications of the MHW-RTG. Figure 6 shows the oxygen inflow that would have occurred without the xenon, and that which is obtained with the xenon sweeping.

In this specific example the xenon is only about 70% effective in excluding the oxygen. In practice, the effectiveness will depend on the distribution of hole sizes. If a xenon fill is to be depended upon to prevent oxygen inflow into the generator, then it appears essential to investigate the leakage hole diameter spectrum involved.

Diffusion Suppression to be Expected Through the Use of Modest Xenon Pressures in the RTG

In a test performed at JPL (Reference 2) it appeared that sublimation of SiGe in an evacuated generator was approximately at free sublimation rates.

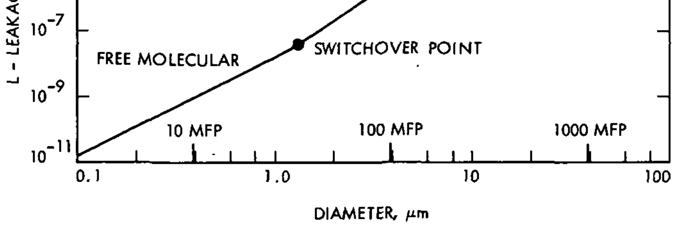

Figure 1. Xenon leakage vs hole diameter

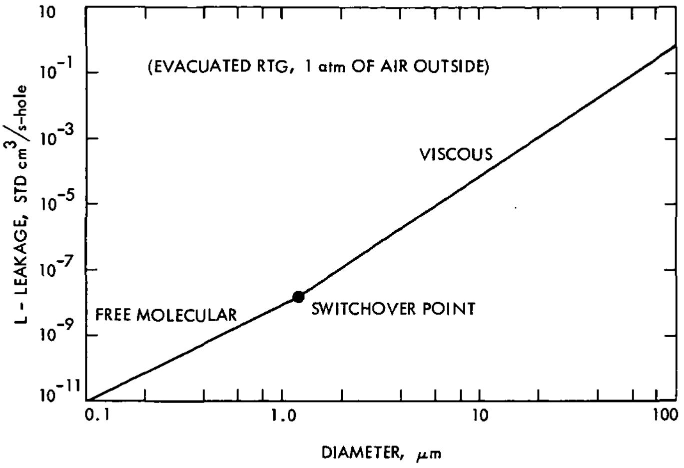

Figure 2. Oxygen in-leakage vs hole diameter

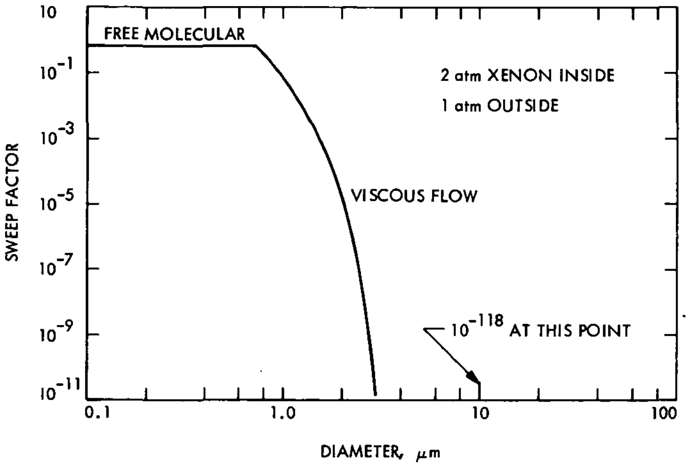

Figure 3. Sweep factor vs hole diameter

It is of interest to determine the extent to which sublimation can be reduced under modest xenon pressures, since it might be feasible to provide modest xenon pressures for extended periods (in the absence of meteoroid damage). The gas-filled incandescent lamp (invented by Langmuir) depends on this mechanism. Low pressure xenon atmospheres might offer sublimation protection without lowering power output excessively. Some lowering of power at BOL might be beneficial since there is an excess of power available, and since a lowering of the hot-side temperature at BOL will result in longer life.

Any xenon baffling effect will work by increasing the pressure of the subliming species next to the solid in question, and by blanketing the solid

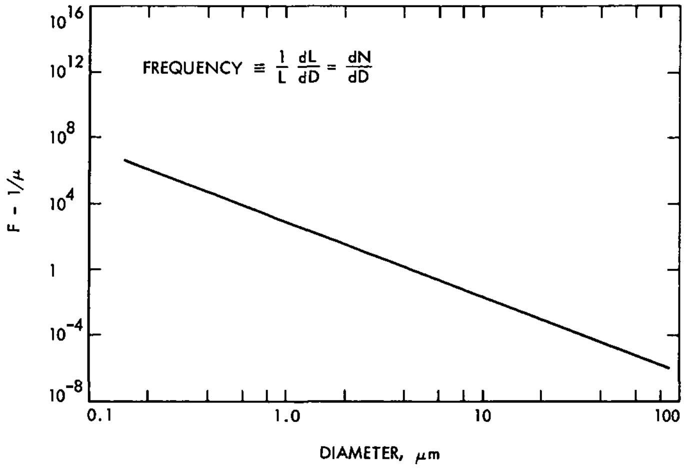

Figure 4. "Frequency" vs hole diameter postulated for example

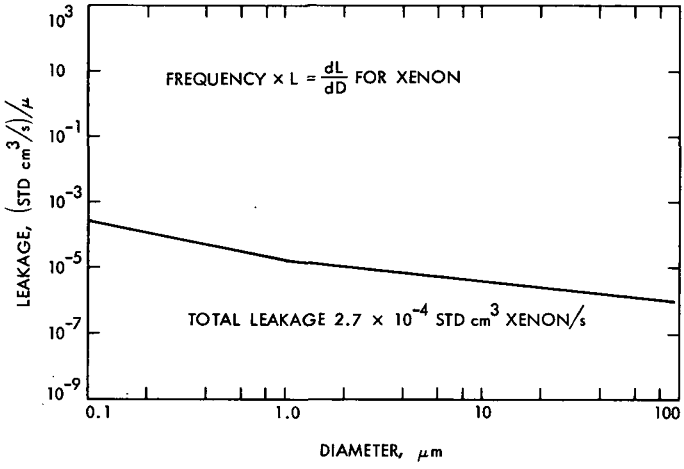

Figure 5. Leakage plot for xenon

with a gaseous diffusion layer that produces a resistance to flow. To estimate the effectiveness of the gaseous diffusion layer requires the determination of the effective thickness of this layer. Two ways of estimating this film thickness are discussed in the next two subsections.

Condensation as a Means of Determining Gradients (Nonreacting Insulation)

From the hot shoe to the cold side of the generator a temperature drop of about 20°C is encountered in the region of interest. If supersaturation is ruled out, this will establish an exponential pressure profile that leads to an effective film thickness of roughly 1.5 mm. If the insulation pore size is large

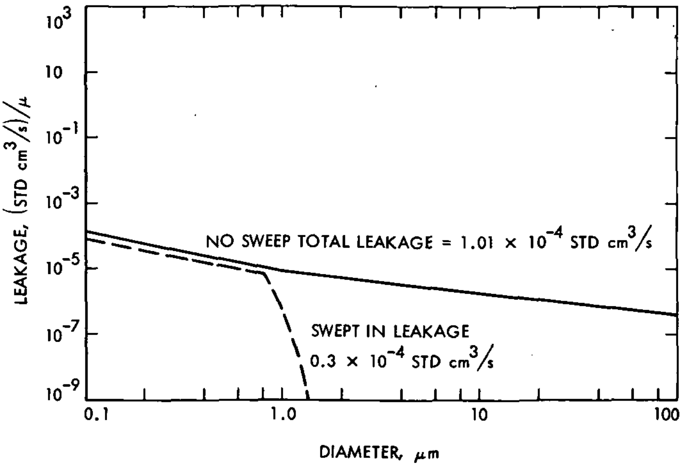

Figure 6. Leakage plot for oxygen

compared to the mean free path of the subliming gas species in the xenon gas, and if the insulation density is very low and the tortuousity in the insulation system is low, then gas diffusivities can probably be safely used to describe the vapor transport. Otherwise a gas flow "conductivity" must be determined for the fibrous insulation.

Reaction with Insulation as a Means of Establishing Gradients

If there is SiO_2 insulation close to the couple, it can take Si vapors and convert them to SiO vapors, which can diffuse away. Only a given amount of insulation can be permitted to corrode away and still have a viable RTG. Probably the film thickness of 1.5 mm determined earlier is a good estimate to use from the "sink" point of view also.

Baffling Effect of Xenon Layer of Effective Thickness *t*

If a subliming material is surrounded by a gas blanket of thickness t through which the species must diffuse, the subliming gas species will assume a pressure at the solid surface somewhere between the equilibrium (saturation) pressure and zero pressure. The rate of diffusion away from the solid (through the gas layer) will be

$$S_d = \frac{D}{t}(P_{act} - 0) \tag{1}$$

where D is the diffusion coefficient of the Si vapor in xenon, t the effective thickness of the gas layer, and P_{act} is the pressure established at the solid/vapor interface.

A material that has a saturation pressure P_{sat}, and is surrounded by a pressure P_{act} of its own species will have a sublimation rate (if we assume a sublimation coefficient of unity) that can be found from Langmuir sublimation with a driving force of $(P_{sat} - P_{act})$.

$$S_{\ell} = \sqrt{\frac{RT}{2\pi M}} (P_{sat} - P_{act}) \tag{2}$$

Equating the mass fluxes S_{ℓ} and S_d, we get

$$\sqrt{\frac{RT}{2\pi M}} (P_{sat} - P_{act}) = \frac{D}{t} (P_{act} - 0) \tag{3}$$

Defining as a baffling (sublimation suppression) factor

$$B \equiv \frac{P_{sat}}{P_{sat} - P_{act}} \tag{4}$$

we obtain, by combining Equations 3 and 4

$$B = \frac{t}{D} \sqrt{\frac{RT}{2\pi M}} + 1 \tag{5}$$

Interestingly enough, no pressure terms appear in Equation 5. There is of course a dependence on the *inert gas pressure*, since the diffusivity D is inversely proportional to it. The baffling (sublimation suppression) factor seems, however, unrelated to the sublimation behavior of the solid in question, so long as the inert gas pressure is higher than the solid saturation pressure.

The first term on the right hand side of Equation 5 is a dimensionless number, the ratio of the Langmuir sublimation flux to the diffusion mass flux (using the same driving forces). Perhaps this is a new dimensionless number. It may be of great usefulness in the understanding of the mechanisms of suppression of sublimation in RTGs. There is no question about the value of R, T, or M. The diffusivity D can be calculated. The only thing in the *dimensionless equation that requires judgment is the estimation of the* effective film thickness t. This follows the "stagnant film" concept pioneered by Langmuir, and now widely used in heat and mass transfer.

Sample Calculations

The most important number to obtain is the diffusivity. The Gilliland equation is probably as good a basis as any.

At 1000°C for Ge/Xe, we get $D_{Ge} = 569/P$ with D in cm^2/s, P in torr. At 1000°C for Si/Xe, we get $D_{Si} = 870/P$.

The baffling factors at 1000°C, using the diffusivities shown earlier, and a thickness t of 0.15 cm, are shown in Table 1. For 1100°C and 1200°C the values are quite close to the ones shown.

These estimates are quite encouraging. A charge of 10 torr of xenon may be quite maintainable, provided there are no leaks caused by meteoroid impacts.

There are several reasons why results are not really of interest for the pressures higher than about 10 torr. Xenon leakage increases with system pressure. At higher pressures thermal shorting will come into play significantly, and it is likely that the baffling factors of 10–15 or so that can be obtained at moderate pressures are high enough to make it unnecessary to bring the temperatures down very much. It also seems unwise to depend on *very* high baffling factors. If one made a design, relying totally on an enormous baffling factor, a leak would be catastrophic. It seems more advisable to design so that a leak will lead only to partially compromised mission objectives.

Mechanization Possibilities of Xenon Systems

It is of interest to postulate methods of ensuring a sufficient supply of xenon to the generator when required, and of depleting it when it is no longer necessary.

It is possible to use individual RTGs that are filled with xenon, with no external plumbing. This has several disadvantages:

(1) There is no xenon reserve except the amount that exists due to the xenon compression.

(2) If RTGs are to be exhausted after launch, each RTG requires an explosive valve.

(3) If, because of mishaps in the launch phase a leak develops in an RTG, the limited reserve could be troublesome since the components of the RTG might oxidize.

One can also connect all the RTGs to a common xenon supply line kept at a given pressure. This has a number of advantages:

(1) The xenon reserve can be made as large as required to prevent troubles with small leaks or launch phase mishaps.

Table 1. Predicted sublimation suppression factor at 1000°C for xenon

Materials	P = 1 torr	P = 10 torr	P = 100 torr	P = 1000 torr
Ge/Xe	2.24	13.4	125	1241
Si/Xe	2.3	14	131	1301

(2) Only one set of valves is required to exhaust the RTGs after launch.

(3) It might become practical to operate the RTGs throughout at least the early part of the mission with some xenon inside to minimize sublimation problems of hot RTG materials.

Xenon lends itself well to compact storage and handling. It can be stored close to its critical point, which is at 58 atm, 17°C. A perfect gas compressed to 58 atm would only be 58 times as dense as at standard temperature and pressure (STP). At the critical point xenon is 184 times as dense as at STP, and it is virtually at room temperature (17°C).

A very lightweight tank will suffice to hold xenon at 58 atm. The tanks JPL uses on the Mariner spacecraft for pressurized nitrogen (attitude control) hold 6.25 l at 190 atm and weigh 2 kg. A tank such as this would hold 6.5 kg of xenon (1000 l at STP), evidently an enormous supply. A schematic of a possible piping arrangement is shown in Figure 7. The helium produced by the radioisotope fuel is shown leaving through glass diffusion barriers, impervious to xenon. High pressure and low pressure regulating systems are shown for ground/flight operation.

Except for the last few hours prior to launch, the tank could be recharged as needed. A regulated manifold can be connected to the individual RTGs. Before launch and after launch, this manifold can be regulated at different pressures as needed. If the RTGs are to be evacuated on purpose for operation in space, explosive valves for evacuation can be tied to the common manifold. Probably two valves are required: first a slow one to get rid of most of the xenon slowly enough to avoid damaging the generators, and second a high throughput valve to provide a large vacuum conductance for the complete evacuation.

In conclusion, the design of a xenon supply system can be done in a straightforward way. It should be noted that unlike other gases, neither the

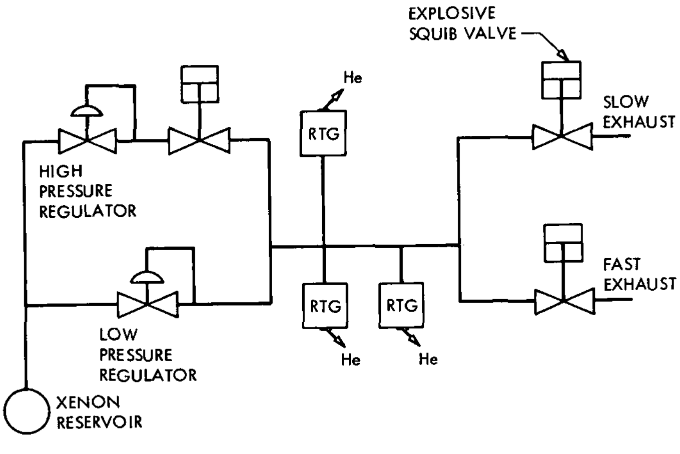

Figure 7. Possible control scheme for xenon supply

xenon weight (6 g/l at STP) nor the cost ($4/l at STP for pure material) is completely negligible.

References

1. de Winter, F., *Use of Protective Xenon Atmospheres in Silicon Germanium Thermoelectric Generators*, Report 900-546 (EM 342-169), Mar. 1972, (JPL internal document).
2. de Winter, F., and G. Stapfer, "Silicon Germanium Technology Program of the Jet Propulsion Laboratory," in *Proceedings of the IECEC*, San Diego, Calif., Sept., 1972.