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The Challenge of Mining He-3 on the Lunar Surface: How All the Parts Fit Together

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Abstract

After the initial confirmation of the existence of He-3 on the lunar surface in 1985, there has been a flurry of activity both in the U.S. and abroad to find the best method of garnering it. The group at the University of Wisconsin has been focusing on a multipurpose lunar miner called Mark II which excavates, beneficiates, heats, then cools, and finally redeposits the soil on the lunar surface. Such a miner will be faced with many challenges in the harsh environment of the moon. One of the more difficult challenges is how to transfer regolith from the lunar vacuum into the interior of the miner operating at some pressure. This paper will examine this issue and seek a solution.

Introduction

Mining helium-3 (He-3) on the lunar surface to be used on earth in advanced fuel aneutronic fusion reactors is beginning to be accepted by many in the world fusion community as an entirely reasonable option. Several studies are confirming the economic viability of this method of providing mankind with a safe and environmentally clean source of energy for many generations to come (Kearney 1990, Thompson 1993). New ideas for fusion devices with configurations which are better suited to take advantage of the benefits of the deuterium-He-3 cycle are starting to appear. Although still a long way to fruition, the seed that was planted some eight years ago is starting to grow.

Since the discovery of He-3 on the moon in 1985, there have been many schemes proposed for extracting it from the regolith. The group at the

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University of Wisconsin has been focusing on a multipurpose lunar miner called Mark II, which excavates, beneficiates, heats, cools and finally redeposits the regolith on the moon while collecting and storing the solar wind products. Over the past four years, several improvements have been proposed specifically in the area of beneficiation. In a paper presented at the ASCE Space'92 conference, it was shown that a fluidized bed can be used to separate the $<50\ \mu$m particles from the excavated bulk regolith. This paper will assess the impact of a fluidized bed on the miner configuration. Another aspect of the design which has not been fully evaluated is the need to separate the vacuum of lunar space from the operating atmosphere of the fluidized bed and the heater zone which follows. Inserting the regolith from lunar vacuum space into the pressurized process zone of the miner is a challenging design requirement, as is the reverse process. The use of a suitable system will be evaluated and the impact on the miner configuration determined.

Description of Mark II Miner

Figure 1 is a CAD (computer aided design) generated picture of the Mark II miner as it is presently envisaged. Perhaps the most prominent feature of the miner is the large 12 m diameter solar collector which is mounted on a cone shaped tower capable of 360° rotation about a vertical axis as well as the ability to tilt the collector about a horizontal axis going through the support gimbal. Energy is beamed to the collector from a large 110 m diameter solar dish mounted at some distance on the lunar landscape. The energy is beamed into the miner and is distributed onto surfaces immersed in liquid sodium. Heat pipes are used to transfer the energy to the regolith.

At the front of the miner a bucket wheel excavator executes a 150° arc as it cuts into the regolith in front of it. The trench which is opened up is 3 m deep and 11 m wide. The regolith is dumped onto a conveyer belt which drops it into the miner onto a set of progressively smaller sieves. All of the fraction which does not pass the sieves is immediately returned to the trench. This can be seen coming out of the first return pipe of which there is one on each side of the miner. The remaining fraction which is reduced to particles smaller than 250 μm now must be transferred from the lunar vacuum to the miner operating pressure. This is accomplished by two power screws or augers. Once inside the miner proper, the regolith is injected into a flowing stream of gas moving at a predetermined velocity. Particles smaller than 100 μm are fluidized and carried upwards in the gas stream. Those that are larger fall down into the bottom of the fluidizing cylinder and are ejected from both sides of the miner into the trench. They can be seen coming out of the second pipe forming a mound on either side of the miner.

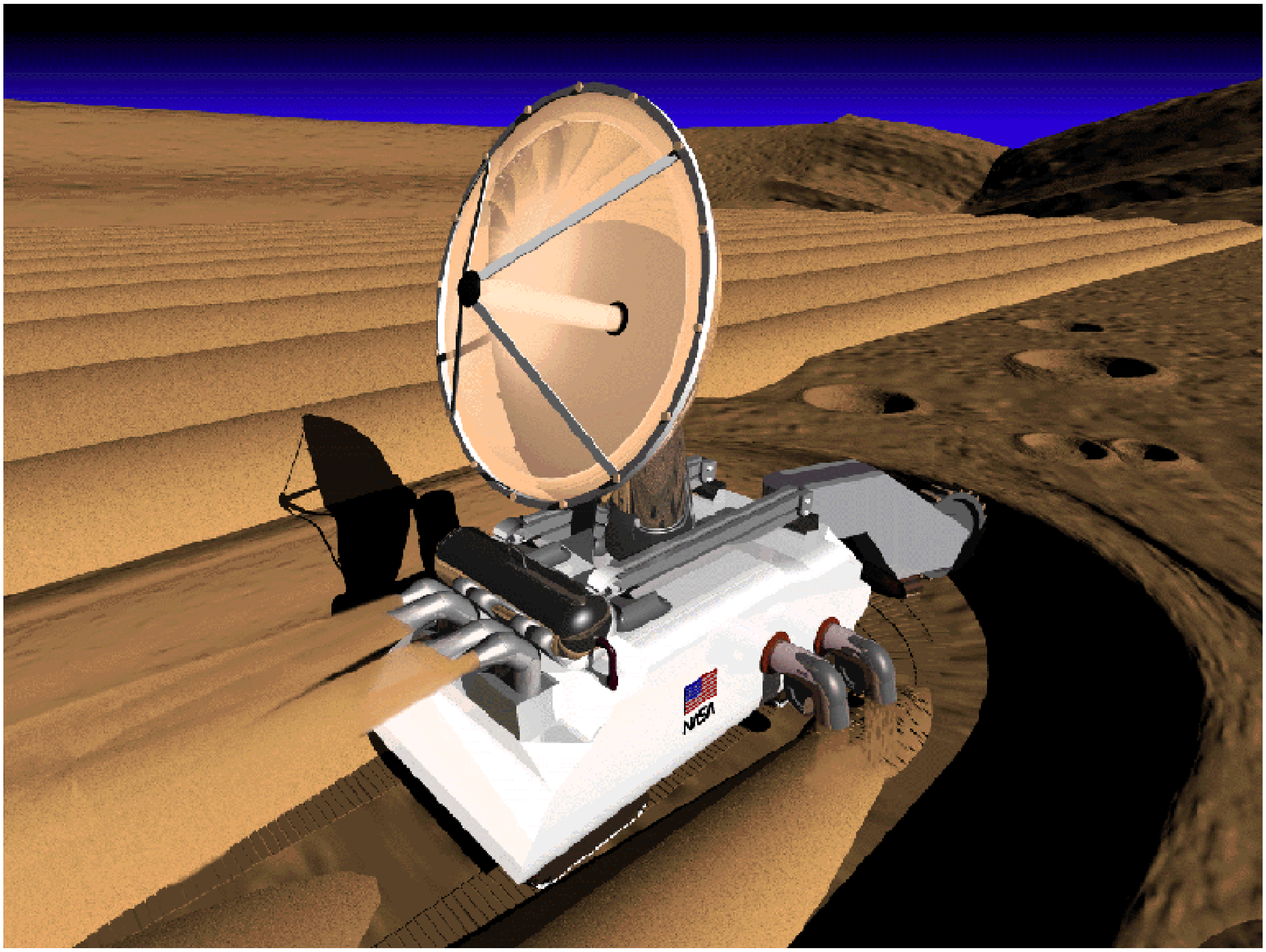

Figure 1. Computer aided representation of the Mark II miner.

The regolith which makes it through the fluidized bed goes through a cyclone separator which centrifugally separates the particles from the gas. The gas goes back to a fan where it is pumped back into the fluidizer cylinder. The regolith, which now consists of particles smaller than 100 μm, is dumped into hoppers which surround a heat exchanger consisting of heat pipes. There are three parts to this heat exchanger, a preheater, a main heater and a recouperator. Some heat pipes shuttle energy from the bottom of the heat exchanger to the top. Thus, energy which is recovered from the hot exiting regolith is transferred to the top of the heat exchanger for preheating the cool incoming regolith. The main heater which is nested between the preheater and recouperator sections of the heat exchanger only supplies the energy which is not recovered by the recouperator, $\sim 15\%$ of the total. This is done by using the collected solar energy for boiling sodium in a boiler connected to a series of heat pipes. The processed regolith, which is only 100° hotter than its ambient temperature on the lunar surface, now goes to a differentially pumped ejection chamber from which it is ejected through reciprocating nozzles out the back of the miner. By reciprocating the ejection nozzles, the trench is filled up relatively uniformly minimizing the effect on the lunar landscape.

Table 1

Pertinent Miner Parameter

Annual collection rate of He-3 (kg)	33
Mining hours per year	3942
Excavating rate (tonnes/hr)	1258
Depth of excavation (m)	3
Forward speed of miner (m/hr)	23
Area excavated per year (km^2/y)	1.0
Processing rate (tonnes/hr)	556
Lunar process energy (MW)	12.3
Heat recovery (%)	85
Estimated operating electric power (kW)	200

As the regolith percolates through the maze of heat pipes which are on a triangular pitch, it is preheated to 600°C, then heated to 700°C in the main heater and finally, cooled to 100°C in the recouperator. The residence time of a particle in the heater is 20 s. During this time, which is very long compared to the diffusion time of gas from the particles, the solar wind products emerge from the regolith and are pumped into high pressure cylinders. One such cylinder is shown on the back of the miner. As the cylinder reaches 20 MPa, it is disconnected and, with the use of manipulators shown on either side of the miner, it is removed and placed on the side of the trench. An empty cylinder is picked up and connected and the miner proceeds forward. Table 1 gives the pertinent parameters of the miner.

Challenges of Lunar He-3 Mining

Probably the greatest challenge of mining He-3 on the moon is that it exists in the lunar regolith in a very dilute form. For example, assuming a 10 ppb concentration, in order to obtain one gram of He-3, the following is needed:

- 150 tonnes of lunar regolith must be excavated
- 66 tonnes of lunar fines must be processed
- 82 GJ of energy must be supplied just for heating.

This leads to some very obvious conclusions which are:

- Handle the regolith as little as possible
- Process only fractions with the highest concentration
- Recycle energy.

These three maxims have thus far guided the design of the Mark II miner. It was decided to use the bucket wheel excavator, which is an efficient digging tool capable of going three meters deep, and providing a large mass throughput of lunar regolith. The regolith is lifted only several meters, inserted into the miner, then travels a short distance through the miner, approximately 15 m and finally is returned to the lunar surface. Only particles of 50 μm-100 μm and smaller are processed since they contain the bulk of the solar wind products. A heater designed to be 85% efficient is used reducing the 82 GJ of energy to only 12.3 GJ. The only materials retained are the solar wind products which are contained in pressure vessels, and the effect on the lunar landscape is a slight fluffing (decrease in density) and a slight rippling.

There are many other challenges that have to be dealt with, some of which are listed below:

- Finding the best source of process energy
- Beneficiating regolith $<$50-100 μm
- Collecting the solar wind products and issues of handling the pressure cylinders
- Issues of tribology and lunar dust
- Working in the vacuum of space.

Some of these issues have been dealt with, albeit in a somewhat cursory way. There is no doubt each one can be the subject of a research paper by itself. In ASCE Space '92 it was shown (Sviatoslavsky 1992) that a fluidized bed can be an effective means for separating different size particles. The impact on the miner is that now, it has to operate at a pressure of 0.1 MPa instead of .01-.02 MPa, as envisaged when an electrostatic precipitator was assumed in the original design. Inserting the regolith from the vacuum of space into the miner at 0.1 MPa is now an issue. This problem will be addressed in the next section.

The Interface Between the Vacuum of Outer Space and the Miner

In the original Mark II miner design, when the operating pressure was low (.01 MPa), a column of regolith $\sim$ 3.5 m long would overcome the internal pressure under the action of the low lunar gravity. As long as the diffusion of gases through the column was lower than the velocity of the regolith, this column acted as a seal between the miner atmosphere and the lunar vacuum. However, with the implementation of a fluidized bed in the miner, the pressure went up by an order of magnitude to 0.1 MPa. Obviously the column of regolith flowing under the force of gravity which is now 35 m long is not practical, and a new method must be devised. Two plans have been looked at, a batch process and a continuous process.

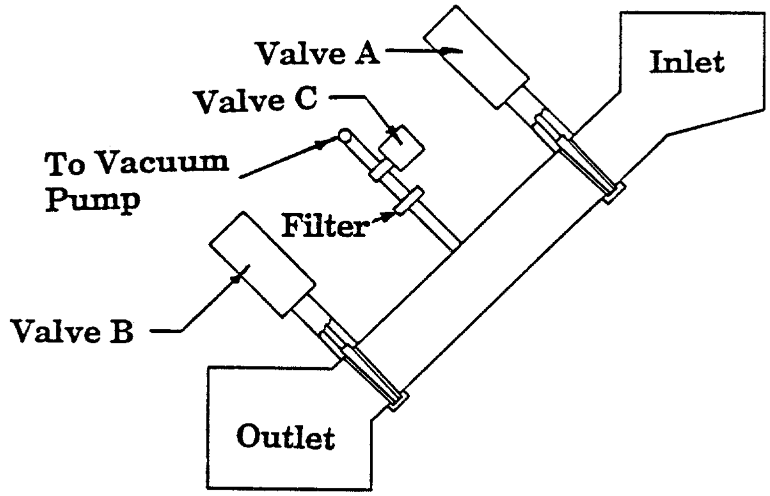

Figure 2. A system for a batch process conveyer.

Batch Process

A batch process by its very nature implies an intermittent delivery. Such a system would not be acceptable for the miner, unless several batch process units are sequenced to insure an uninterrupted supply of regolith to the fluidized bed. The number of units needed depends on the mechanism used to implement the process, and a cursory look suggests that at least three are required.

Although there are many batch processes used in the chemical industry, the one examined in this study is specifically designed to minimize the loss of solar wind products to the lunar vacuum. Figure 2 is a schematic representation of the system. A certain predetermined volume is contained in a duct between automatic valves A and B. The volume is connected to a vacuum pump through a filter and a valve C. The process begins with the volume evacuated to some value of pressure on the order of 10^{-3} torr. Valve A opens allowing regolith from the supply hopper to fill the volume, and then valve A closes. Valve C leading to the vacuum pump is closed and valve B is opened. As the pressure in the volume equalizes with that in the miner, the regolith flows out under the action of gravity. At this time, valve B is closed and valve C opened and the volume is evacuated by the vacuum pump, starting a new cycle.

If three of these units are used, the vacuum pump would be connected to each through three separate valves. Then, as one volume is being filled with regolith, the second volume is emptied of regolith and the third volume is being pumped out. The volumetric throughput will be essentially determined by the

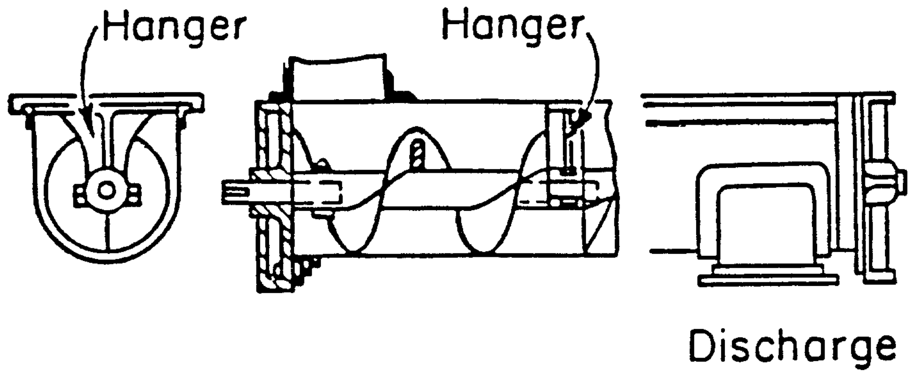

Figure 3. A typical power screw conveyer system.

capacity of the vacuum pump which controls the rate at which the volume can be evacuated.

The main issue with this scheme is the ability of the valves to seal. Typically, gate valves of the kind needed here are not very good at sealing. This is only exacerbated by the presence of the lunar regolith fines which will coat the surface of the seal.

Continuous Process

The continuous process investigated here utilizes a power screw or auger which effectively overcomes the force of pressure exerted on the regolith by the gases in the miner. One of the advantages of a power screw is that it can be used in many orientations, i.e. inclined with the regolith lifted, or lowered, or it can be used horizontally as well. Figure 3 is a typical power screw conveyer shown in a horizontal attitude.

A standard formula taken from an engineering handbook [Baumeister and Marks, 1958] gives the power requirement for such a system as a function of volumetric throughput, density of material, diameter of screw, revolution rate, length of conveyer and a factor which is determined by the kind of material being transported. This formula which was converted from English units to SI units is shown below:

$$P(kW) = 2.84(ALN + CWLF) \times 10^{-6} \quad (1)$$

where A is a factor having to do with screw size and bearing friction, and has the units of kg/revolution, L is the length of the screw in m, N is the RPH (revolution per hour), C is the volumetric throughput in m^3/h, W is the density in kg/m^3 and F is a dimensionless friction factor which is determined by the type of material being transported. For our case we have used the material group containing silica sand as a semi-abrasive material with a friction factor of 2.0.

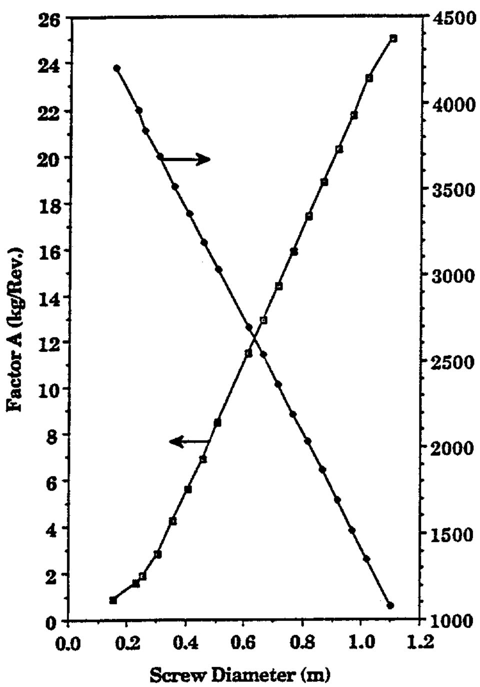

Figure 4. Factor A and allowable RPH as a function of screw diameter.

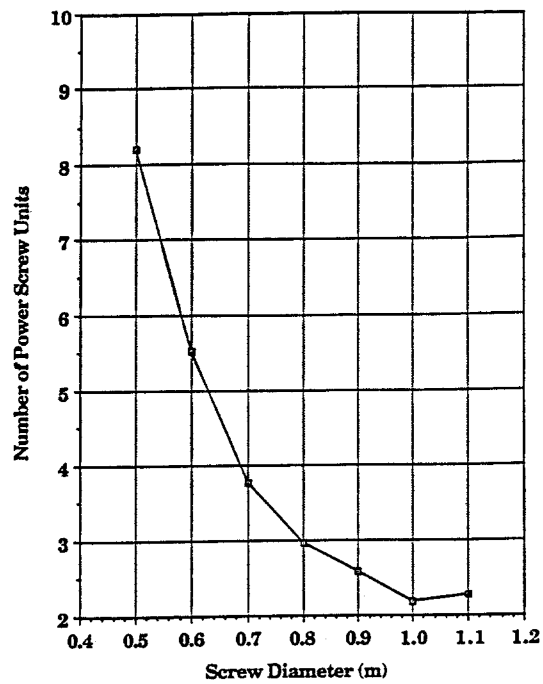

Figure 5. Number of power screws needed to convey 310 m^3/h of lunar fines as a function of screw diameter.

As can be seen this formula makes no allowance for a difference in pressure. In order to include this pressure difference, the formula was modified with an equivalent density W_e in this manner:

$$P(kW) = 2.84(ALN + CWLF + CW_eL) \times 10^{-6} \,. \qquad (2)$$

The first term (ALN) accounts for bearing friction, the second ($CWLF$) for friction of the transported material, and the third term (CW_eL) for the power needed to overcome pressure.

Figure 4 shows the factor A and the recommended RPH for the given group of materials as a function of the screw diameter (Baumeister & Mark, 1958). Figure 5 shows the number of power screw units needed to transmit 310 m^3/hr of regolith fines as a function of the screw diameter. This curve was generated taking into account the maximum recommended RPH and the maximum recommended area cross section of the screw occupied by the regolith which is 25% for this group of materials. It is interesting to note that the curve actually reaches a minimum at a screw diameter of 1.0 m and then starts to rise. The curve shows that 3 units of 0.8 m diameter will be needed or four units of 0.68 m diameter.

Using Eq. (2) and assuming a 1.2 m screw length, it was found that the power requirement for the 3 units of 0.8 m diameter is 13.1 kW and for the 4 units of 0.68 m, it is 13.2 kW, essentially the same. However, it is interesting to note that by splitting the distance in two and evacuating the intermediate space with a vacuum pump to 0.05 MPa, a method called staging, the pumping power is reduced to 7.1 kW and 7.27 kW for the two systems respectively. A 90% efficiency of the motor has been used. It is also interesting to note that 84% of the power is needed to overcome the pressure difference, 10% to overcome material friction and 6% for machinery friction.

The power requirement of the vacuum pump needed for staging depends on the diffusivity of the lunar regolith. For example, the diffusivity of a loose packed dry sand of 50% porosity is 2×10^{-11} m^2 while that of dry earthen soil is 3×10^{-13} m^2 (Scheidegger, 1974). At 2×10^{-11} m^2 and a driving force of .05 MPa, He gas will diffuse through 38% void regolith at 0.62 m/s and at 3×10^{-13} m^2 it is 0.0093 m/s. Both of these velocities are lower than the regolith velocity in the conveyer of $\sim$ 1.4 m/s for both systems. The vacuum pump is estimated to have a capacity of 10 liters/s and will require 0.55 kW for a ΔP of 0.05 MPa. High efficiency filters will be needed to insure that dust does not collect on vacuum pump components.

System Interfacing or How All the Parts Fit Together

In the above section a scheme was described for conveying the regolith across the vacuum boundary. The screw discharge is near midway of the miner height and would be appropriately located for injection into the fluidized bed. The fluidized bed (Sviatoslavsky, 1992) consists of a vertical cylinder 1.5 m in diameter and 3 m high. It has He or H_2 gas at 0.1 MPa flowing upwards at a velocity of 0.24-0.3 m/s which is the terminal velocity for fluidizing particles of $< 100\,\mu$m. As the particles caught in the gas stream move upwards they are deflected to the periphery of the cylinder by a cone on the top of the cylinder. Here the cylinder converts to a cyclone separator where the centrifugal force separates the particles from the gas. At this elevation the particles enter the chutes leading to the heater.

After going through the heater, the particles which are now on the lower level of the miner are conveyed across the vacuum boundary by staged power screws. For minimizing solar wind product losses the intermediate stage is kept at $\sim$ 10 torr, keeping the losses to $< 0.1\%$. The power requirement of these screws is modest, < 1 kW. At this point the regolith must be elevated about 2 m and dropped onto rotating paddles which eject it through nozzles back onto the lunar surface.

Incorporation of the fluidized bed complicates the conveyance of the regolith into and out of the miner atmosphere; however, it actually simplifies the overall handling of the regolith. An electrostatic beneficiator requires two additional particle lifts, one before and one after the beneficiator, whereas the fluidized bed accomplishes this in one step. It can be concluded that a fluidized bed is compatible with the scheme of the miner and that all the parts seem to fit together well.

Conclusion

It has been shown that a staged power screw is suitable for conveying regolith from the lunar vacuum into the miner at 0.1 MPa and back to lunar vacuum. Four screws of 0.68 m in diameter and 1.2 m long will be capable of conveying the 310 m^3/h of lunar regolith fines. Losses can be maintained to $< 0.1\%$ of the solar wind products and the total power requirement for all the power screws and vacuum pumps is ~ 10 kW. A batch process has been looked at but was rejected due to the problems envisaged with the gate valves operation. A fluidized bed seems compatible with the miner system and actually streamlines somewhat the handling of the regolith throughout. Issues of concern are dealing with lunar dust and erosion of the power screw components.

Acknowledgement

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