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Atomic Oxygen Concentrators for Material Exposure Acceleration Tests in Low Earth Orbit

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Atomic oxygen concentration technology was investigated with two types of concentrators. One is a "horn-type" and the other is a "multiple ring-type" concentrator. Both of them were designed with a computer simulation using a hard-cube model. It was made clear that the primary factor for limiting the concentration factor is the gas buildup near the focal point. In the ground test using a laser-detonation source, which gave an intense atomic oxygen beam pulse, the concentration factor of 2–3, which is lower than the theoretical expectations, is obtained. However, it is suggested that the low concentration factor is due to the recombination reaction of atomic oxygen into molecular oxygen by the high peak flux in the pulsed atomic oxygen beam. The flux limit of the concentration factor is not a case in the real low Earth orbit space environment, and the multiple ring-type concentrator can be expected to achieve a concentration factor of over 40 in a low Earth orbit exposure condition.

Nomenclature

A	=	area of quartz
C	=	concentration factor
d	=	thickness of quartz
E	=	energy
F	=	flux
f_0	=	resonant frequency
$N(t)$	=	number of atoms arrived at the time of t
$P(E)$	=	number of atoms with translational energy of E
t	=	flight time
Δf	=	change in resonant frequency
Δm	=	change in mass
ρ	=	density of quartz

I. Introduction

SINCE atomic oxygen-induced erosion phenomena in low Earth orbit (LEO) were recognized, much effort for the development of atomic oxygen-resistant material has been carried out for more than two decades. Recent progress in polymer chemistry enables one to synthesize the atomic oxygen-resistant polymers [1]. To verify the survivability of such atomic oxygen-resistant materials in space environment, high-fluence atomic oxygen exposure tests have to be conducted. Such a high-fluence test in LEO is not realistic because the required test period becomes unacceptably long. This is also the same situation even for the ground-based tests. Thus, atomic oxygen concentration technology will be useful for the atomic oxygen-resistant material tests both in LEO and on the ground. However, atomic oxygen is a noncharged species such that any electromagnetic optics, which is widely applied to focus ions and electrons, cannot be applied to concentrate atomic oxygen. The only practical method to change trajectories of a noncharged particle is using reflecting surfaces. Such an atomic oxygen-focusing device has already been evaluated by the space shuttle flight STS-85 in 1997. Three parabolic horns with three different sizes have been tested to collect atomic oxygen for acceleration testing of materials. However, it has been reported that the concentration factors were lower than the expectations [2].

For the high-fluence atomic oxygen exposure tests, we have reported an attempt for establishing atomic oxygen concentration technology [3,4]. In the previous report, the relationship between material selection or shape of the reflecting surface and concentration efficiency has been studied. It was made clear that the use of a material with a low recombination coefficient of atomic oxygen into molecular oxygen is important to increase the efficiency. It was also demonstrated that the computer simulation for the atomic oxygen trajectories in the inelastic scattering event at the reflecting surface is advantageous to focus atomic oxygen.

In this study, we designed two types of atomic oxygen concentrator devices to concentrate atomic oxygen based on the results of previous studies. These concentrators were designed to achieve a small deflection angle of atomic oxygen to preserve translational energy of atomic oxygen beams. The performance of these devices was evaluated by a laser-detonation atomic oxygen beam source. Advantages and limitations of these devices to material exposure tests were also discussed.

II. Atomic Oxygen Beam Facility

The laser-detonation atomic oxygen source was used in this experiment. Figure 1 shows a schematic drawing of the fast atomic oxygen beam facility including the beam diagnostic system used in this study [5–7]. The atomic oxygen source is based on the laser-detonation phenomenon and was originally developed by Physical Sciences, Inc. [8,9]. This type of atomic oxygen source uses a pulsed CO_2 laser (5 J/pulse) and a pulsed supersonic valve (PSV). The laser light is focused on the nozzle throat with the concave Au mirror located 50 cm away from the nozzle. The PSV introduces pure oxygen gas into the nozzle and the laser light is focused on the oxygen gas in the nozzle. The energy for the dissociation of the oxygen molecule to oxygen atom and the acceleration of atomic oxygen are provided by the multiphoton absorption process. The atomic oxygen beam, thus generated, was characterized by a time-of-flight (TOF) distribution measured by the quadrupole mass spectrometer installed in the beam line. Translational energies of the species in the beam were calculated using TOF distributions with a flight length of 181 cm. We used the relationship of the transitional energy distribution $P(E) \propto t^2 N(t)$ to calculate the translational energy. The mean energy of the hyperthermal atomic oxygen was approximately 5 eV.

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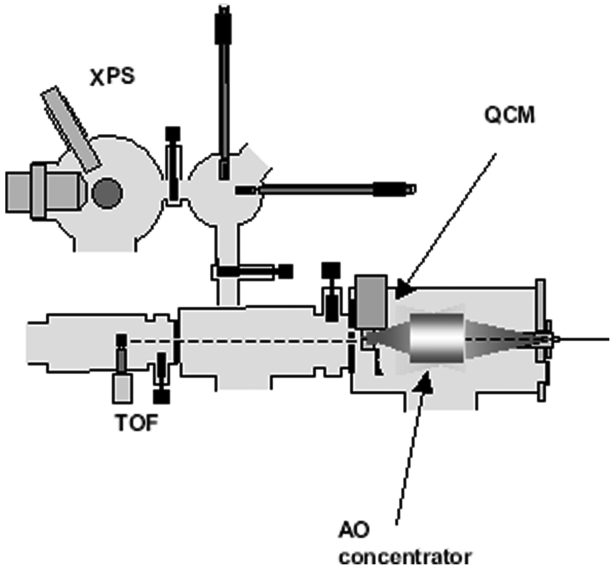

Fig. 1 Schematic drawing of the laser-detonation source and the test configuration of the concentrators; AO: atomic oxygen; XPS: x-ray photoelectron spectrometer.

A silver-coated quartz crystal microbalance (QCM) was used to measure atomic oxygen flux at the focal point of the concentrators [10]. The temperature of the QCM sensor was maintained at 38 ± 0.1°C by the temperature-controlled circulating water system. The reaction efficiency of atomic oxygen with a silver film was calculated from the frequency shift of QCM with the equation

$$\Delta f/f_0 = -\Delta m/(\rho A d) \tag{1}$$

For the QCM sensor crystals ($f_0 = 5$ MHz) used in this study, the change in resonant frequency is expressed by the following equation:

$$\Delta f = -2.26 \times 10^{-6}(f_0^2 \Delta m)/A \tag{2}$$

where Δf and f_0 are given in Hz, Δm in g, and A in cm^2. Thus, for the QCM with a resonant frequency of 5 MHz, 0.1 Hz of Δf corresponds to 2 ng. It is clear from Eq. (2) that the detection of adsorbate with a mass resolution of nanogram level can be achieved by using QCM [11]. A typical atomic oxygen flux used in this study was 10^{13}–10^{15} atoms/cm^2/s.

III. Atomic Oxygen Concentrators

Two types of atomic oxygen concentrators were designed and tested. One is made of Pyrex which is a material showing the lowest recombination coefficient of atomic oxygen [12]. The overall shape of the concentrator is a horn such that it is called a "horn-type" concentrator (Fig. 2). The curvature of the reflecting surface was designed by the computer simulation with a hard-cube model reported previously [3,4]. Because of the energy loss at the scattering event, the shape of the reflecting surface is slightly different from the parabolic horn. The inlet diameter is 45 mm, the outlet diameter is 13 mm, and the length is 100 mm. The surface roughness of the reflecting surface is $Ra = 16$ nm. The theoretical concentration factor, which is given as the ratio of the areas of the inlet and the outlet, is 11.98. For comparison purposes, a simple cone-shape concentrator was also tested. The dimensions of this "cone-type" concentrator are inlet diameter: 50 mm, outlet diameter: 10 mm, length: 100 mm, and surface roughness: $Ra = 21$ nm. The theoretical concentration factor is 25.

The design concept of the second concentrator is to minimize the gas buildup at the focusing region. To reduce the gas buildup effect, the reflecting surface was removed near the focal point. The left panel of Fig. 3 shows a photograph of the cut model of the "multiple ring-type" concentrator. The trajectories of atomic oxygen scattered at the reflection surface are shown in the right panel. This type of concentrator consisted of four deflection rings. The inlet and outlet diameters of each ring are as follows: ring 1 (72.71 mm, 52.33 mm),

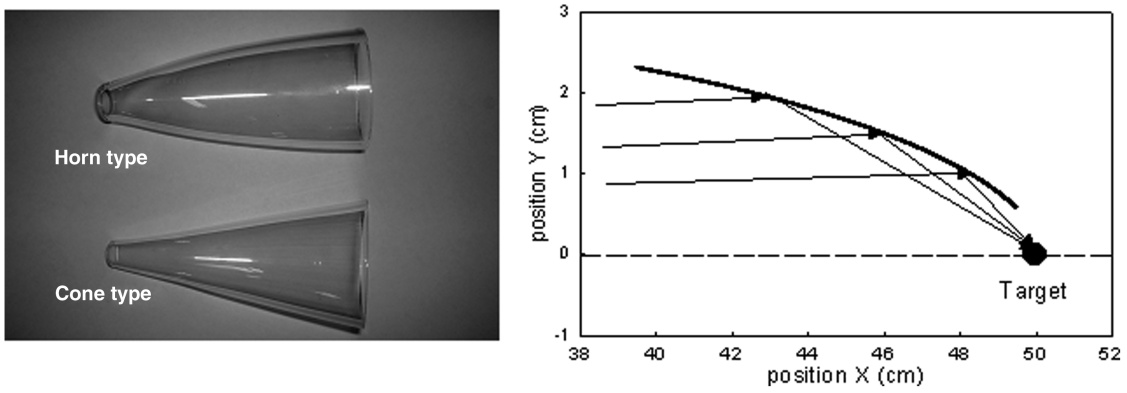

Fig. 2 Photograph of the "horn-type" and the "cone-type" concentrators (left) and the computational trajectories of the scattered atomic oxygen in the horn-type concentrator (right).

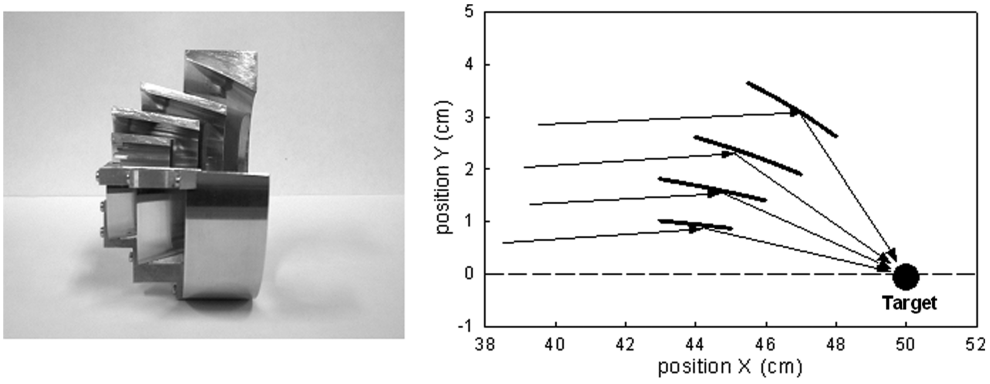

Fig. 3 Photograph of the cut model of the "multiple ring-type" concentrator (left) and the computational trajectories of the scattered atomic oxygen (right).

Table 1 Comparison of the concentration factors of horn-type and cone-type concentrators

Concentrator	Concentration factor		
	Theoretical	Measured	Efficiency, %
Horn type	11.98	2.97	24.8
Cone type	25.00	3.39	13.2

Normal flux: 6.34×10^{14} atoms/cm^2/s

ring 2 (52.00 mm, 37.85 mm), ring 3 (36.00 mm, 27.72 mm), and ring 4 (20.00 mm, 17.13 mm), respectively. These rings are made of aluminum; however, the reflecting surface was covered by silicon dioxide. The theoretical concentration factor of this concentrator is as high as 64.5.

IV. Results and Discussion

A. Horn-Type Concentrator

Table 1 compares the performance of the horn-type and the cone-type concentrators. The test was made by an atomic oxygen beam with a flux of 6.34×10^{14} atoms/cm^2/s. It is clearly indicated that the atomic oxygen flux increases with the use of concentrators. Absolute atomic oxygen flux with a cone-type concentrator is greater than that of a horn-type concentrator. This result seems to show that the computer-aided design is not an accurate method to use for designing the concentrator; however, this is simply due to that fact that the inlet diameter of the cone-type concentrator is greater than that of the horn-type concentrator. The advantage of computer-aided design is indicated in the concentration efficiency which is the ratio of actual and theoretical concentration factors. The efficiency of concentration of the horn-type concentrator is 25%, which is twice as high as the cone-type concentrator (13%). However, these experimental values are small compared to those of theoretical ones. This is probably due to the recombination reaction of atomic oxygen into molecular oxygen by the gas buildup at the outlet area, which was pointed out in the case of the atomic oxygen-focusing device aboard STS-85 [2].

B. Multiple Ring-Type Concentrator

The theoretical concentration factor of the multiple ring-type concentrator depends on the combination of the concentration rings. Figure 4 shows the actual atomic oxygen fluxes measured at the focal point of the concentrator with different combinations of the concentration rings. The atomic oxygen flux without concentrator is 6.5×10^{14} atoms/cm^2/s. The abscissa of Fig. 4 indicates the total area of the reflection rings. It is clearly indicated that the atomic oxygen flux increases with increasing the reflection area. However, it reaches 1.2×10^{15} atoms/cm^2/s in maximum. The maximum concentration factor with four concentration rings is as low as 1.8 compared with its theoretical value of 64.5.

C. Flux Dependence of Concentration

One of the important concerns as a limitation factor of concentration is the recombination of atomic oxygen into molecular

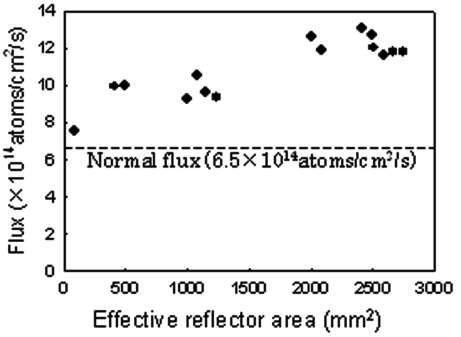

Fig. 4 Atomic oxygen fluxes concentrated by the multiple ring-type concentrators with different reflecting surface areas.

oxygen through three-body recombination reactions. Pressure increase near the focal point is considered to be a primary factor especially for the multiple ring-type concentrator because there is no solid wall near the focal point. If this hypothesis is true, the concentration factor should depend on the average mean free path of atomic oxygen. However, it is not easy for the laser-detonation source to adjust the atomic oxygen flux at the fixed position. Therefore, the flux dependence of concentration efficiency is investigated by placing the metal mesh in front of the concentrator. The atomic oxygen flux through the metal mesh was calculated by multiplying the atomic oxygen flux without metal mesh and the aperture ratio of the mesh. Recombination of atomic oxygen at the mesh surface was not taken into account. The flux dependence tests were carried out for both horn-type and multiple ring-type concentrators. The results are shown in Fig. 5. Figure 5a is the result for the horn-type concentrator and Fig. 5b is that for the multiple ring-type concentrator. As clearly indicated in Fig. 5, the concentration efficiency increases with lower fluxes for both concentrators, but the effect is more obvious for the multiple ring-type concentrator. The solid lines in the figures are the best-fit curves of the data points with inverse exponential functions. Concentration factors C for the horn-type and multiple ring-type concentrators are expressed by the following formulas, respectively:

$$C = 4.0 \exp(-3.8 \times 10^{-16} F) + 1.0 \tag{3}$$

$$C = 38.3 \exp(-6.8 \times 10^{-14} F) + 1.9 \tag{4}$$

It is clearly indicated that all data points agree well with the solid lines in Figs. 5a and 5b. This experimental finding suggests that the concentration efficiency is governed by a physical phenomenon which shows the flux (pressure) dependence by an inverse exponential function. The collision event of the gas molecule is such a physical phenomenon. It was considered that the recombination probability of atomic oxygen is proportional to the collision density of atomic oxygen, which is inversely proportional to the mean free path. From the discussion here, the flux dependence of the concentration factor can be explained as follows: the recombination reaction of atomic oxygen became dominant when the pressure of

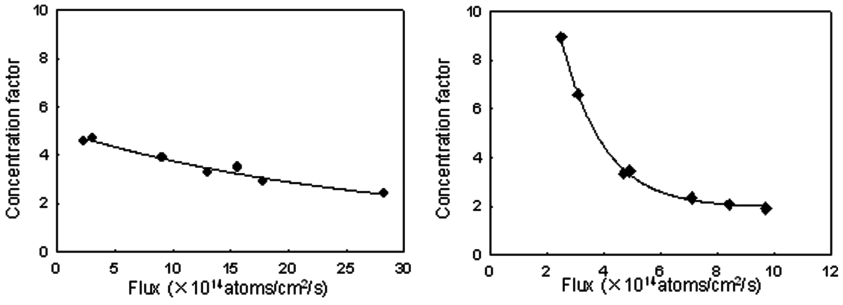

Fig. 5 Flux dependence of the concentration factor: a) horn-type concentrator and b) multiple ring-type concentrator.

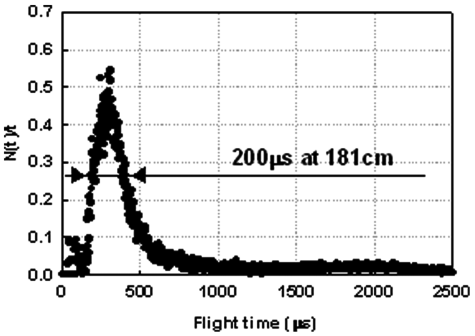

Fig. 6 Typical time-of flight spectrum of the atomic oxygen beam used in this experiment.

atomic oxygen at the focal point increased. This is because the collision event of atomic oxygen increases exponentially with increasing the pressure. The recombination of atomic oxygen into molecular oxygen self-terminates the maximum concentration efficiency of the concentrators.

The concentration factors without the effect of recombination reaction are estimated by the extrapolation of the experimental data. The concentration factors without the recombination effect were evaluated to be 5.0 and 40.2 for horn-type and multiple ring-type concentrators, respectively. The large concentration factor of the multiple ring-type concentrator is due to the absence of the reflection surface near the focal point, and this inhibits the recombination reaction at the solid surface.

D. Concentration Performance in a Low-Earth-Orbit Environment

As shown in Table 1 and Fig. 4, the concentrators designed in this study show concentration factors of approximately 2–3 in the ground-based experiments using laser-detonation source. These values are even smaller than those reported by the STS-85 mission which was made in the slightly low atomic oxygen flux condition (2×10^{14} atoms/cm^2/s at 290 km) compared with this study (6.3×10^{14} atoms/cm^2/s). We have discussed the performance of the concentrators developed in this study in a real LEO space environment. The major difference in the atomic oxygen exposure condition between the laser-detonation atomic oxygen source used in this study and the real LEO environment is the atomic oxygen density. In LEO, atomic oxygen is supplied as a "continuous beam"; in contrast, the laser-detonation atomic oxygen source generates a "pulsed beam." Fluxes of both beams are in the same level (10^{14}–10^{15} atoms/cm^2/s). This is an average flux in 1 s; however, the recombination reaction occurs in a much shorter time scale and it is governed by a peak flux. Figure 6 shows a typical TOF spectrum of the atomic oxygen beam generated in the laser-detonation atomic oxygen source. This spectrum is measured at 181 cm from the nozzle, and the flux measured by Ag-QCM is 6.3×10^{14} atoms/cm^2/s. It is obvious that the width of the atomic oxygen peak is approximately 200 μs. Because the peak width is considered to be proportional to the distance from the nozzle, the peak width at 48.5 cm (concentrator position) is expected to be approximately 54 μs. If the peak shape is assumed to be a steplike function, the peak intensity of the atomic oxygen peak at concentrator position is 3.7 times greater than that at 181 cm. Because atomic oxygen arrives at the focal point in 54 μs, the peak flux of atomic oxygen reaches as high as 1.2×10^{19} atoms/cm^2. This peak flux is 5 orders of magnitude greater than the continuous beam. Because the recombination efficiency of atomic oxygen is governed by the peak flux, it is considered that the concentration factors measured in this study are strongly affected by the flux limit. In other words, the peak atomic oxygen flux in LEO is 5 orders lower than the experimental condition in this study, and it affects much less the concentration performance of the concentrators. Thus, the concentration factor of 40 is expected for the multiple ring-type concentrator in a real LEO exposure condition.

V. Conclusions

Atomic oxygen concentration technology was investigated with two types of concentrators. One is a horn-type and the other is a multiple ring-type concentrator. Both of them were designed with a computer simulation using a hard-cube model. It was made clear that the primary factor for limiting the concentration factor is the gas buildup at the focal point. In the ground test using a laser-detonation source, which gave an intense atomic oxygen beam pulse, the concentration factor is strongly limited by the recombination reaction; however, this is not the case in real low Earth orbit space environment. The multiple ring-type concentrator is expected to show the concentration factor over 40 in a LEO environment.

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References

[1] Brunsvold, A. L., Minton, T. K., Gouzman, I., Grossman, E., and Gonzales, R., "An Investigation of the Resistance of Polyhedral Oligonomeric Silsesquioxane Polyimide to Atomic Oxygen Attack," *High Performance Polymers*, Vol. 16, No. 2, 2004, pp. 303–318. doi:10.1177/0954008304044121

[2] Final Report, United States Developed ESEM Experiments, "Evaluation of Space Environment and Effects on Materials," http://setas-www.larc.nasa.gov/esem/AOE.html.

[3] Tagawa, M., Matsumoto, K., Doi, H., and Yokota, K., "Atomic Oxygen Concentration Using Reflecting Mirrors," *Proceedings of the 7th International Symposium on Protection of Materials from a Space Environment* (to be published).

[4] Tagawa, M., Matsumoto, K., Doi, H., and Yokota, K., "Computer Simulation and Its Experimental Verification of Atomic Oxygen Concentration," *Journal of Spacecraft and Rockets*, Vol. 43, No. 5, 2006, pp. 999–1003. doi:10.2514/1.15037

[5] Tagawa, M., and Yokota, K., "Polyimide Erosion in Low Earth Orbit Space Environment," *Journal of Adhesion Science and Technology, Polyimides and Other High Temperature Polymers: Synthesis, Characterization and Applications*, edited by K. L. Mittal, VSP, Utrecht, Vol. 3, 2005, p. 553.

[6] Yokota, K., and Tagawa, M., "Comparison of Polyethylene and Polyimide as a Fluence Monitor of Atomic Oxygen," *Journal of Spacecraft and Rockets*, Vol. 44, No. 2, 2007, pp. 434–438. doi:10.2514/1.15038

[7] Tagawa, M., and Yokota, K., "Synergistic Study on Atomic Oxygen-Induced Erosion of Polyethylene with 172 nm Vacuum Ultraviolet," *Journal of Spacecraft and Rockets*, Vol. 41, No. 3, 2004, pp. 345–349. doi:10.2514/1.10888

[8] Caledonia, G. E., Krech, R. H., and Green, B. D., "A High Flux Source of Energetic Oxygen Atoms for Material Degradation Studies," *AIAA Journal*, Vol. 25, No. 1, 1987, p. 59. doi:10.2514/3.9580

[9] Caledonia, G. E., and Krech, R. H., "Energetic Oxygen Atom Materials Degradation Studies," AIAA Paper 87-0105, Jan. 1987.

[10] Matijasevic, V., Garwin, E. L., and Hammond, R. H., "Atomic Oxygen Detection by Silver-Coated Quartz Deposition Monitor," *Review of Scientific Instruments*, Vol. 61, No. 6, 1990, pp. 1747–1749. doi:10.1063/1.1141145

[11] Tagawa, M., Yokota, K., Kinoshita, H., and Ohmae, N., "Application of Quartz Crystal Microbalance for Polymer Degradation Studies Regarding Atomic Oxygen Activities in Low Earth Orbit," *Proceedings of the 9th International Symposium on Materials in a Space*, ESA, Noordwijk, The Netherlands, 16–20 June 2003, SP-540, pp. 247–252.

[12] Greaves, J. C., and Linnet, J. W., "The Recombination of Oxygen Atoms at Surfaces," *Transactions of the Faraday Society*, Vol. 55, 1959, p. 1323.

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