SAND90-2368C

Compaction and permeability of simulated waste[1]

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ABSTRACT: This paper focuses on the mechanical and hydraulic properties of simulated contact handled transuranic radioactive waste that are associated with the Waste Isolation Pilot Project (WIPP). In particular, the mechanical behavior of the simulated (nonradioactive) waste and its permeability after substantial time dependent compaction are being measured to give input data for modeling contaminated brine flow in a geologic repository stratum.

A number of deformation and permeability tests have been performed on materials comprising this waste. A variety of material mixtures were used, including cloth, wood, metals (various geometries), plastics, and minerals (various grain size distributions). Prior to the permeability tests, specimens were loaded under a constant stress (2000 psi) from 1 to 50 days and allowed to achieve a stable density state. Specimens, four inches in diameter with various lengths, were loaded axially via a piston and confined radially by the pressure vessel cylinder wall. Axial deformation was measured for production of stress-density and density-time curves. Subsequent to the deformation stage, which was terminated after evidence of density stabilization, brine was passed through the specimen for permeability measurements.

Deformation and permeability measurements of the simulated waste material are presented. Permeability values ranged through several orders of magnitude.

1.0 INTRODUCTION

1.1 *Project Overview*

The Waste Isolation Pilot Project (WIPP) facility, near Carlsbad, New Mexico, is currently being evaluated for the purpose of storing contact handled and remotely handled transuranic radioactive waste.
Characterization of the mechanical and hydrological properties of the waste is important for predicting the repository behavior with time. More specifically, the potential for migration of groundwater through the

[1] This work was supported by the United States Department of Energy under Contract DE-AC04-76DP00789

[2] A U.S. DOE Facility

storage areas and the dispersal of radioactive materials must be established. The radioactive waste to be stored in the WIPP facility consists of a variety of materials, including metals, combustibles (plastics and fibers) and "sludge". A large portion of these materials will be contained in 55 gallon drums and stored in rooms that will be backfilled. Because most of the materials initially have high porosities, they will be highly permeable. However, over time the drums may be expected to collapse due to volume decreases in the rooms because of creep-closure. Under these conditions the waste will compact, leading to a reduction in porosity and permeability (Butcher, 1989).

This paper summarizes the results of a series of experiments performed to investigate the time dependant compaction and permeability of simulated waste materials. The experiments were limited to ambient laboratory conditions. Permeability measurements were only performed on compacted specimens. Procedures, equipment, and data from these studies are presented and the results are discussed.

2.0 PROGRAM PLANNING

Butcher (1989) identified five major waste components: plastics, fibers (cellulosics: paper, cloth, wood, etc.), sorbents, metals, and sludge. The results from earlier 55-gallon drum testing (Butcher et al., in preparation), together with information on the anticipated waste inventories, were used to select mixtures of some of the waste components for the tests discussed here. Certain additional materials were also tested. These included granular limonite and magnetite, which were chosen to represent metal materials after decomposition, a mixture of granular magnetite and steel, representing an intermediate corrosion state, and a mixture of shredded metal and crushed salt, which is being considered as an engineered alternative to untreated wastes. These mixtures are described by their respective weight percentages in Table 2.1.

Table 2.1: Specimen Summary

MATERIAL NUMBER	MATERIAL DESCRIPTION
1	39% Intact and sectioned bottles, 42% PVC Conduit, 19% Surgeons Gloves
2	40% Rags, 60% Pine wood cubes (1" dimension)
3	60% 1" dimension steel, 40% crushed salt
4	45% Material 1, 37% Material 2, 9% 1" dimension metals, 9% Dry Portland Cement
5	Magnetite granules (coarse, well graded)
6	Limonite granules (coarse, well graded)
7	50% Magnetite particles, 50% 1" dimension steel
8	80% crushed salt, 20% shredded metals

3.0 EXPERIMENTATION

Two uniaxial strain compaction and brine permeability tests were run on each of the materials in an oedometer to a maximum axial stress of approximately 2000 psi, the estimated lithostatic pressure at the repository horizon.

Because the mechanical and hydrological properties of the simulated contact handled transuranic waste were thought to be variable through a broad range, a laboratory measurement system had to be assembled that accomodated acceptable precision and accuracy at extreme levels of strain and permeability. System reliability was another concern due to the lengthy nature of most tests (weeks to months), specimen transience (i.e., destructive testing), corrosive properties of the saturating brine, and rigid quality assurance requirements.

To alleviate some of these concerns, a redundancy in data collection was assured by incorporating several transducers into the meaurement system. For example, three pressure transducers and two flowmeters were put in the permeability flow circuit; thermocouples were placed in the fluid reservoir enclosure and on the pressure vessels. In this manner, back-ups were available in case the primary transducer failed, and additionally, a larger range of measurement was realized by using two or more transducers with different ranges, without sacrificing significant precision or accuracy.

3.1 *Specimen Preparation*

All specimens were assembled according to weight percent specifications, photographed, and mixed together in the pressure vessel. A "random" yet well mixed blend was attempted for most of the specimens (e.g., particulate matter and small components), while other specimens were packed in specific configurations due to the specimen component size and composition (e.g., metal blocks and particulate matter). After specimen insertion brine was introduced into the pressure vessel chamber to saturate the specimen. The brine consisted of a prototypical chemistry, designed to simulate in situ water chemistry after several thousand years of waste emplacement.

3.2 *Compaction System*

Apparatus for these tests consisted of an oedometer (pressure vessel) used as the sample holder, a load control system for maintaining constant axial stress, a flow control system for permeability testing, and instrumentation to monitor loads, deformations, and brine flow.

Samples were contained in a 4" ID, 6" OD steel pressure vessel fitted with an integral axial piston to provide axial stress (Figure 3.1). The axial piston assembly attached to the bottom of the sample holder, and extended to the hydraulic pressure system through a standard dog-bone strain gaged load cell. Both the top end-piece and the bottom piston were pierced to allow flow of brine through the sample; mesh screens were used at either end of the sample to allow brine flow without extrusion of any sample material.

Hydraulic pressure to the axial piston system was provided by a gas control system consisting of an a gas/hydraulic bladder accumulator backed by a nitrogen bottle. Both the accumulator and the nitrogen bottle were in an insulated enclosure, with temperature controlled at 24 to 26 °C. Load on the sample was monitored using a strain-gaged load cell, with backup provided by a pressure transducer in the hydraulic pressure line.

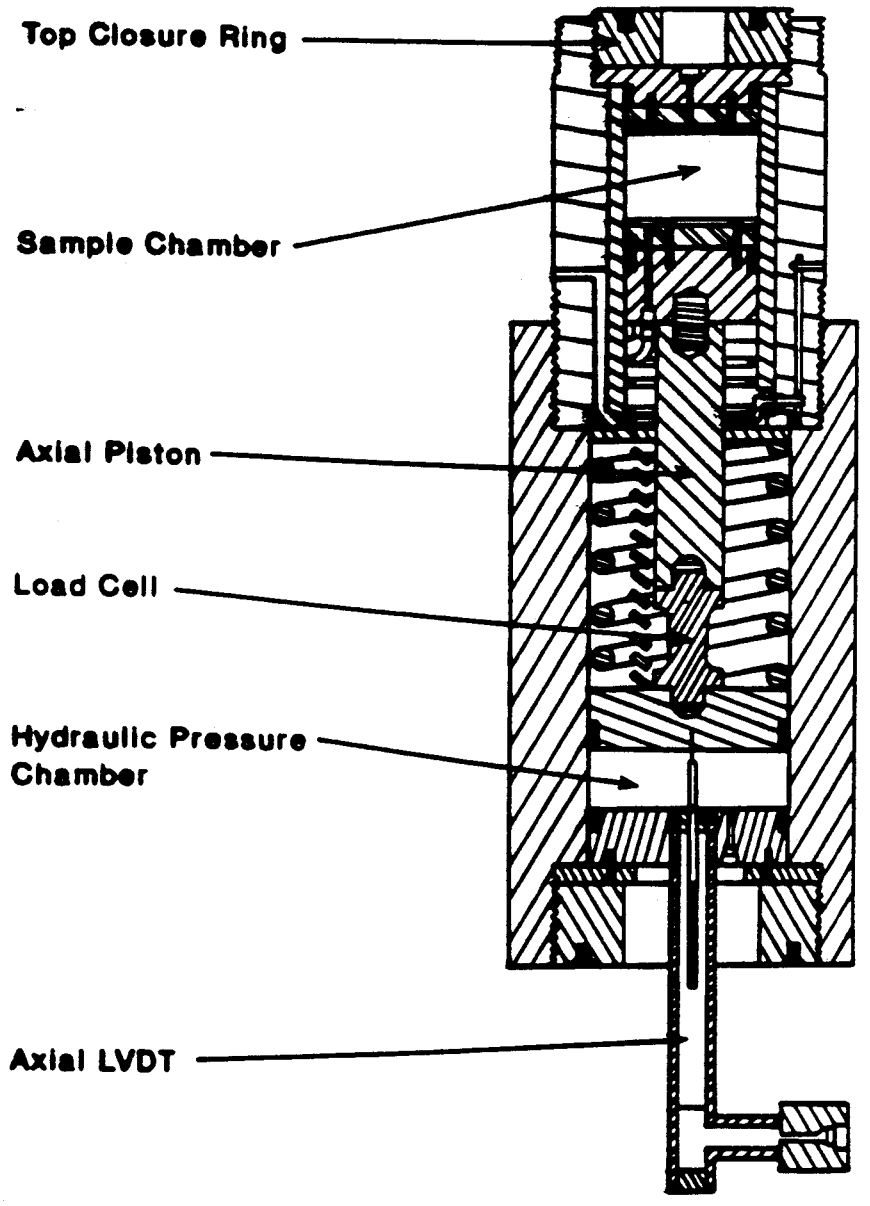

Figure 3.1: The oedometer setup for compaction and permeability testing.

Axial deformation was monitored with a 4" stroke LVDT attached to the lower loading piston. Temperature of the vessel during the tests was monitored using a thermocouple.

Load was applied to the axial piston by pressurizing the bladder accumulator to the required gas pressure, then slowly opening the valve to the piston assembly until the required hydraulic pressure and axial load were achieved. Axial load, line pressure, temperature, and sample deformation were monitored during specimen loading. On achieving full load the gas and hydraulic fluid pressures were maintained for the duration of the test while monitoring compaction. In the longer term tests load was held constant until a density/time slope of approximately 10^{-5} gm/cm^3/hr was obtained, or until the specified test duration was reached. Final density/time slopes ranged from 1.2×10^{-8} to 3.9×10^{-6} kg/m^3/hr. The duration of the tests varied from 1 to 59 days.

3.3 *Permeability System*

Brine permeability was determined at the end of the constant stress compaction portion of the tests . Brine flow was initiated by pressurizing an accumulator using a nitrogen bottle and controlled via a metering valve. Flow rate and pressure drop were monitored, and upstream pressure adjusted until a constant flow was established within the range of the flow meter and pressure transducer. In several tests different flow rates were used. Good agreement was obtained between the two flow measuring devices. Pressure difference between the upstream and downstream sides was monitored using one of three available upstream pressure transducers, with ranges of 25, 100 and 1000 psi.

3.4 *Data Acquisition System*

All instrumentation outputs were monitored using an IBM compatible 8086 computer with an internal clock, and a 16-bit analog-to-digital converter. Data were stored on hard disc, and backed up periodically onto a floppy disc.

Prior to testing, all instrumentation, including the load cells, LVDTs, pressure transducers, and flowmeters, were calibrated. Additional system calibrations were performed on the permeability measurement system, including a flow rate-pressure calibration for the flow lines.

Data were acquired at different frequencies during the tests. During the initial portion of the compaction test when specimen loading was relatively rapid, the automated DAS acquired data every 20 seconds then decremented the rate to a minimum of one scan every hour during the latter stages of compaction; a total of four scanning rates were used through each test.

3.5 *Equipment Limitations*

The equipment had limitations imposed by the resolution of the instruments, which determined the lower bound of measurable permeability, and by the friction in the lines which imposed an effective upper bound on the permeabilities. The flowmeter has a resolution of 0.0036 cc/s, based on the resolution of the voltmeter and the calibration constant for the instrument. The accuracy of the LVDT float system, including electronic noise, is +/- 0.005 liters: this translates to an accuracy of the order of 0.083 cc/s over a 60 second reading, or 0.0083 cc/s over 600 seconds.

A practical upper limit for permeability is reached when the pressure drop through the specimen is not significantly different than the pressure drop through the tubing. This is true because, as the pressure drop becomes dominated by the tubing, the correction for tubing flow resistance (some delta pressure value) involves the subtraction of two similar values and approaches zero. The upper limit is seen as an increase in uncertainty as the conductivity of the sample approaches that of the tubing, the actual limit depending on the relative values of these specimen conductivities and their individual uncertainties. Related to tubing (flow) friction was an upstream filter to remove particulates from the brine; early in the test series this filter was positioned downstream of the pressure transducers. Since this added additional line pressure loss, the filter was moved upstream of the pressure transducers for later tests of high permeability materials.

4.0 RESULTS

4.1 *Time Dependent Compaction Results*

The compaction results for the various tests are presented in Table 4.1. Stress/density and density/time plots are given for the two plastics specimens that exhibited the most extreme changes in density values (Figures 4.1 and 4.2). Data in the tables are presented in terms of the densities and porosities of the materials at various times during the tests.

The compaction curves for the earlier tests show a periodic variation in density. This is not temperature related, but is a function of the early load control system. In the earliest tests the bladder accumulator used for pressure control was isolated from the back up nitrogen bottle. Due to the small volume of fluid in the system, early compaction and small system leaks, reductions occurred in hydraulic pressure which were adjusted manually on a daily basis, and are seen as density fluctuations in the plots. Despite these periodic variations the overall curves follow a regular trend and can be smoothed to give needed time dependent compaction parameters, such as those discussed by Butcher (1989). In later tests the control system was modified to give continuous back up to the nitrogen bottles. Smoother time dependent compaction curves were observed with this system. In some of the compaction curves, especially for the magnetite and limonite, irregular curves are seen. This is believed to be a true effect, which is exaggerated in the plots because of the small density changes involved.

4.2 *Permeability Results*

Permeability results are given in Table 4.1. Typical data acquired by the automated DAS for permeability testing are shown in Figures 4.3 and 4.4. Brine permeabilities were determined on all samples at the end of the time dependent compaction phase by flowing brine through the samples and recording flow rate and pressure.

Slopes of the permeability calibration curves (flow rate versus pressure drop, exemplified in Figure 4.4), designated here as K_l, were used to correct the measured permeabilities. The correction is applied by treating the lines (K_l) and sample (K_s) as two elements in series so that:

TABLE 4.1

MATERIAL DESCRIPTION	SPECIMEN TYPE #	TEST #	TEST DURATION (hours)	Initial DENSITIES (kg/m^3)	Final DENSITIES (kg/m^3)	Initial POROSITY[2] (%)	Final POROSITY[2] (%)	DENSITY/ TIME SLOPE $(kg/m^3/hr)^3$	PERMEABILITY (mD)
Wood/Rags	2	1	243	184.3	933.8	83.3	15.4	3.2×10^{-6}	17
	2	6	330	200.6	808.0	81.8	26.7	5.4×10^{-8}	>71
Plastics	1	2	325	290.3	1042.0	71.0	-4.2	1.4×10^{-8}	No Flow
	1	11	643	309.7	970.7	69.0	2.9	1.2×10^{-8}	99
SPEC. 1, 2,	4	3	430	343.1	1092.0	71.6	9.6	3.6×10^{-7}	63
metals, cement	4	10	973	378.3	979.4	77.1	4.1	3.3×10^{-8}	45
Steel cubes/ crushed salt	3	5	383	1181.0	2003.0	69.0	47.4	6.8×10^{-8}	27
Magnetite	5	7	26	2429.0	3134.0	53.3	39.7	3.5×10^{-7}	109
granules	5	12	24	2540.0	3121.0	51.2	40.0	3.9×10^{-6}	1096
Limonite	6	8	28	1454.0	2046.0	46.1	24.2	6.8×10^{-8}	93
granules	6	13	24	1430.0	1996.0	47.0	26.1	3.1×10^{-8}	1136
Magnetite gran./	7	9	24	1883.0	2696.0	69.9	56.9	7.2×10^{-7}	88
steel cubes	7	14	24	1808.0	2728.0	71.1	56.4	2.0×10^{-7}	8
Shredded metal/	8	15	1414	1168.0	1917.0	53.4	23.4	1.6×10^{-8}	100-5000[2]
crushed salt	8	16	1414	1165.0	2260.0	53.5	9.8	1.6×10^{-8}	151

NOTES: [1] Porosities were calculated using assumed values for solid densities. Uncertainties in these assumed values result in large uncertainties at low calculated porosity, leading to calculated small (or negative) values.
[2] A range of permeability values indicates that steady-state conditions were poorly defined during the test.
[3] Taken from latter (time) stage of density/time curve.

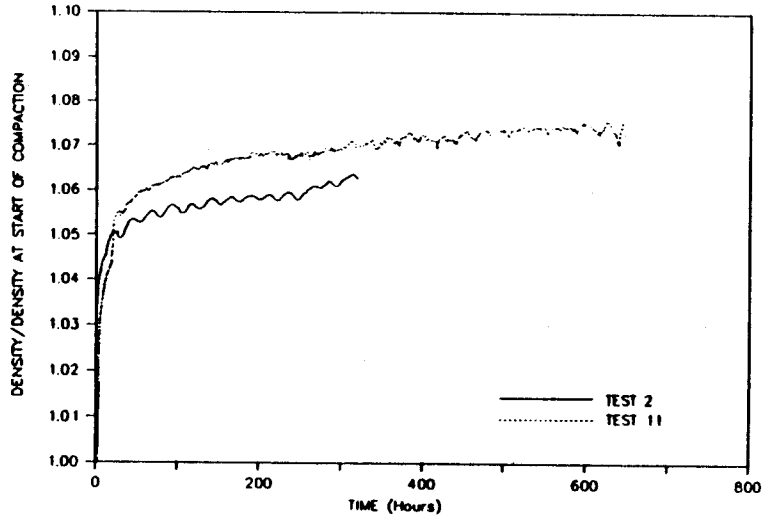

Figure 4.1. Change in density with time of simulated plastics waste at a constant stress of 2000 psi.

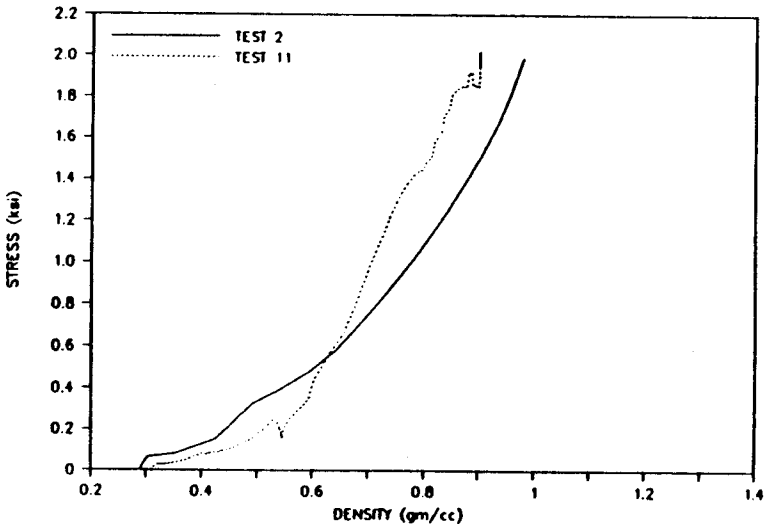

Figure 4.2. Change in density with applied axial stress of simulated plastics waste.

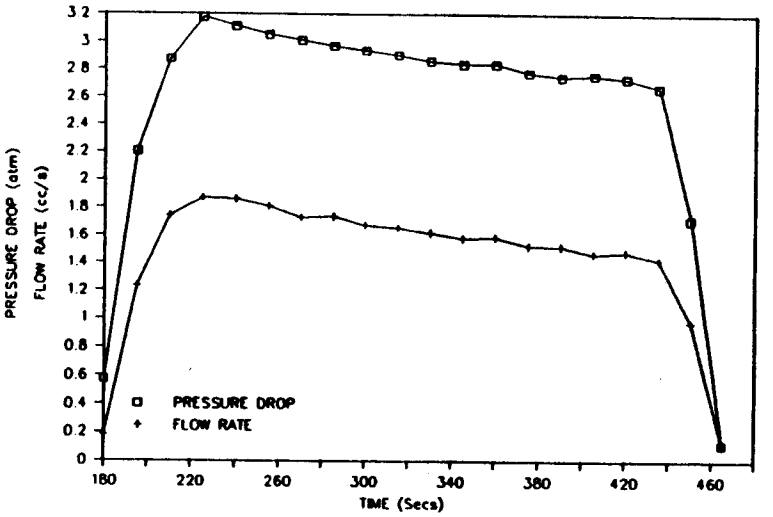

Figure 4.3. Permeability test history for simulated plastics waste.

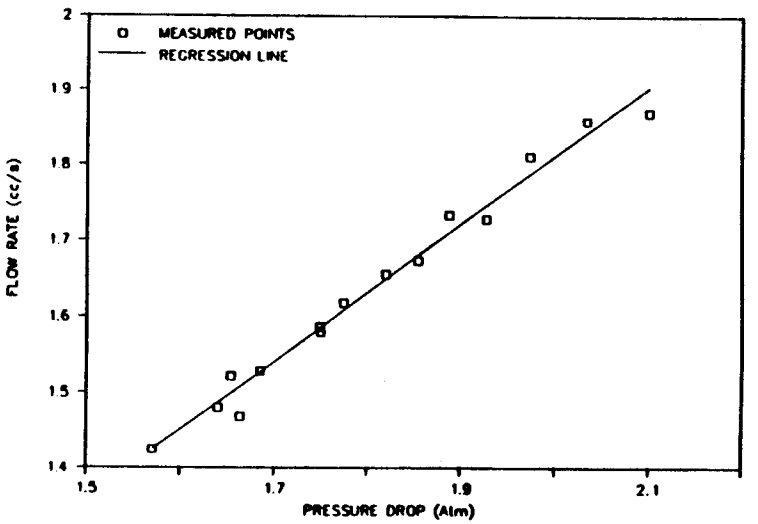

Figure 4.4. Flow rate – pressure drop relationship for simulated plastics waste.

(1) $1/K_s = 1/K' - 1/K_1$,

where K' is the slope of the Q (flow rate) vs. dP (pressure difference) plot. Sample permeability, k_s, is then calculated from Darcy's Law:

(2) $k_s = (Q/dP).v.L_s/A_s$, and

(3) $k_s = K_s.v.L_s/A_s$,

where:

A_s is the sample area (internal area of the sample holder) = 81.073 cm^2

L_s is the sample length (determined from the original sample height and the axial deformation determined during the load up and time dependent compaction tests)

v is the viscosity of brine (assumed to be 1.2 cp at 25 °C).

Permeabilities for the various tests have in general been calculated from the slopes of the pressure difference (dP) - flow rate (Q) curves, this method having the advantages of allowing a check on the linearity of the results, and of removing the effects of small offsets in the pressure or flowrate data. In one test, magnetite and steel cubes, the flow rate was too small for this method to be used. Here an average of the flow rate/pressure drop (Q/dP) values over the stable portion of the test was used to determine permeabilities. In another test, shredded metal and crushed salt, the permeability of the sample varied by large amounts during the flow test, and point by point permeabilities were calculated.

5.0 CONCLUSIONS

A series of uniaxial strain time dependent compaction and brine permeability tests was performed on materials simulating wastes to be stored at the WIPP site. Some of the materials were designed to simulate the long term corrosion products of metal waste and steel drums. One specimen was made up of crushed salt mixed with shredded metals to simulate an alternate form of metallic waste.

All of the materials tested show increasing density and decreasing porosity when loaded in an oedometer to an axial stress of 2000 psi. All of the materials showed some time dependent compaction under constant stress. Final porosities were low for the plastics (less than 5%) but remained quite high for the limonite and magnetite samples (25% to 57%). Final time dependent compaction density/time slopes of the order of 10^{-6} to 10^{-8} $kg/m^3/s$ were reached in 24 to 1400 hours.

Brine permeabilities determined at the end of the compaction stage, while still under an axial stress of 2000 psi, varied with materials, and were quite variable between different samples of the same materials. Most of the waste materials had permeabilities of the order of 10 to 100 millidarcies. Granular magnetite and limonite had permeabilities of the order of 100 to 1000 millidarcies, while the values for crushed salt and metals varied from less than 100 to over 1000 millidarcies. It should be noted that the various granular materials had large grain sizes to intentionally represent worst case scenarios with respect to permeability.

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