AN EVALUATION OF SNOWMELT LYSIMETERS
IN AN ARIZONA MIXED CONIFER STAND

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INTRODUCTION

Snowmelt simulation models may be helpful to resource management planning within the high elevation, mixed conifer forests of Arizona where snow is the primary source of streamflow. However, before any model can be reasonably applied, local testing and calibration is needed to adapt it to regional climatic differences. One approach to testing models on small areas is to use volumetric snowmelt lysimeters of the type developed by Haupt (1969). Environmental and forest stand characteristics can be intensively measured at lysimeter sites and related to snow accumulation and snowmelt, while data variation, inherent in most drainage areas, is reduced.

Snowmelt lysimeters have not been used under stand and climatic conditions common to Arizona's mixed conifer forests, although they have been used successfully on deeper snowpacks of Idaho (Haupt 1969) and Colorado (Schultz 1973), and on the shallower packs of Arizona's ponderosa pine zone (Jones et al. 1976). Our objective was to evaluate the reliability of lysimeters and related installations. This is necessary before meaningful model testing can begin.

STUDY AREA

The study was conducted on the North Fork of Thomas Creek in eastern Arizona, in the Apache-Sitgreaves National Forests. The 467-acre watershed supports an uneven-aged, multistoried, virgin, mixed conifer forest. The major species are Douglas-fir (Pseudotsuga menziesii), ponderosa pine (Pinus ponderosa), white fir (Abies concolor), Engelmann spruce (Picea engelmannii), southwestern white pine (P. strobiformis), quaking aspen (Populus tremuloides), Gambel oak (Quercus gambelii), corkbark fir (A. lasiocarpa var. arizonica), and blue spruce (P. pungens). Douglas-fir is the most common species.

Elevations on Thomas Creek range from 8,400 to 9,250 feet. Topography varies, with the lower and middle portions being relatively steep. The watershed has deep to moderately deep, medium textured, rocky soils, which are derived from basalt parent material. Annual precipitation, measured at a recording precipitation gage near the mouth of the drainage, averaged (with standard error) 27.53 $\pm$ 1.45 inches from 1963 to 1978. Approximately 40% of the precipitation falls as snow from November through April. Annual runoff, measured at a 120°, V-notch weir, averaged 2.63 $\pm$ 1.05 inches from 1966 through 1978. Thomas Creek 1978 (the year of study) winter precipitation was 13.41 inches for the main gage and 13.22 inches for a secondary recording gage at the upper end of the watershed. The watershed received snow during the warm storm of February 28-March 4, 1978, which produced rain-on-snow conditions in lower elevation forests.

The three, neighboring lysimeter sites were on the southeast facing slope, in the upper third of the watershed. Each site was selected to represent low, average, or high forest stand density (based on basal area). The low density site also represents conditions commonly found after timber harvesting using the selection method. Characteristics of each lysimeter site are listed in table 1.

Table 1.--Characteristics of the three lysimeter sites on the North Fork of Thomas Creek (Stand data is per acre).

Site number[1]	97	83	95
Density level	High	Medium	Low
Basal area (ft^2)	338	206	131
No. trees ($\leq$6.9 in. d.b.h.)	287	359	522
No. trees ($\geq$7.0 in. d.b.h.)	318	203	40
Total no. trees	605	562	562
Stem density[2]	5,376	4,025	2,194
Major species	Douglas-fir	Douglas-fir	Ponderosa pine
(by basal area)	Ponderosa pine	Ponderosa pine	Southwestern White pine
	White fir	Quaking aspen	Douglas-fir
Aver. slope	8	27	14
Aver. elev.	9,045	8,930	8,975
Aver. max. temp. (1/28-4/30/78)	39^{0} F	43^{0} F	46^{0} F
Aver. min. temp.	18^{0} F	21^{0} F	23^{0} F
Aver. daily aver. temp.	28^{0} F	32^{0} F	34^{0} F

[1] Site numbers refer to the nearest permanent timber inventory point.

[2] Stem density, the summation of diameter breast height per acre is a good index of solar radiation transmission (Miller 1959).

MATERIALS AND METHODS

LYSIMETER DESCRIPTION

Three lysimeters were installed on each of the three sites. The lysimeter consisted of a 17- by 23-inch sheet metal trough, 6 inches deep, which collected melt water percolating down from a vertical snow column above it (figure 1). The snow column was defined by a vertical frame attached at the four corners and braced 30 inches above the ground. The frame served as a guide along which a cutter was inserted to separate the lysimeter from the rest of the snowpack. The cutter created a vertical air space which prevented extraneous melt water from running into the unit. Haupt (1969) and Schultz (1973) used polyethylene barriers to prevent inflow into their lysimeters; however, this technique was unsatisfactory in Arizona, where several accumulation and melt cycles occur during a winter.

Melt water percolating out of the snow column passed through 4 inches of litter, humus, and mineral soil placed in the trough to simulate the surface structure and initial moisture conditions outside the lysimeter. The top edge of the trough was extended one half inch above the forest floor to prevent extraneous inflow. Two inches of pea gravel and a fine mesh screen separated the soil from the drain at the trough's lowest point. Melt water passed through the surgical tubing to a 5-foot section of 12-inch diameter culvert which was equipped with a water level recorder. The stilling well was charged with 1 gallon of antifreeze at the beginning of the winter. The well had a capacity of 15 inches of melt water; however, a drain was present to release excess amounts and to prevent overflow and loss of records.

DATA COLLECTION AND ANALYSIS

Every week, National Forest personnel changed the stage recorder charts, recut the vertical air space between the lysimeter and the surrounding snow, and measured the snow depth and water equivalent (WE) of the lysimeter snow column. Snowpack WE was determined indirectly by measuring the snow depth at each corner of the frame and then multiplying the average by a snow density obtained from snow tube measurements in the vicinity of the lysimeter. New snowfall during the preceding week was determined by measuring the depth and WE of the snow on a white board which was cleaned and placed on the snow surface each week. The crew also recorded the weekly maximum and minimum temperatures for each site. These temperatures for each site were related by regression analysis to the daily temperatures recorded on thermographs located on the adjacent South Fork drainage. A recording precipitation gage, in a clearing about 1,300 feet southwest of the lysimeter area, also provided useful information.
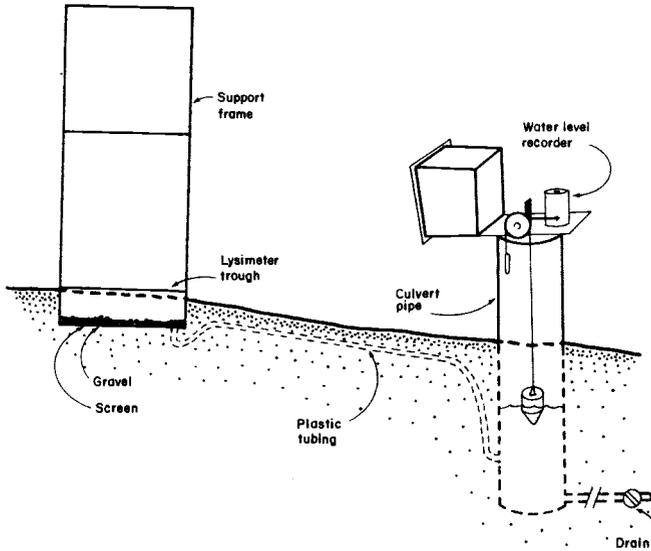
Figure 1.--Schematic diagram of recording snowmelt lysimeter installation.

Stage recorder charts were interpreted in the office using standard procedures. Forest stand information was collected at four points on each site using plotless sampling techniques based on a 25 basal area factor gage.

RESULTS AND DISCUSSION

LYSIMETER OPERATIONS

Lysimeters were installed in 1976 in preparation for the 1977 winter. However, because of poor snowpack (75% of normal) and normal temperatures, the surgical tubing connecting the lysimeter to their tanks froze.

To remedy this situation, the following year the tubing was passed through a 3/8-inch diameter garden hose. The jacketted tubing was then surrounded with a layer of garden grade vermiculite, wrapped in black plastic and reburied. There were no problems in 1978, although the good snowpack did not allow a rigorous test of this technique. In 1979, a blockage occurred at the point where the hose entered the stilling well on one lysimeter, a place which is difficult to insulate, broke the hose connection, and caused the loss of runoff data. This area was reinsulated in preparation for the 1980 season.

The soldered drain plugs also had problems in 1979. These connections failed on four stilling wells, usually when the drains were bumped or manipulated. The use of wooden plugs prevented record loss, and the connections were resoldered in the spring.

EVALUATIONS OF SNOWMELT RUNOFF

Total lysimeter runoff and its timing varied (table 2). The variation among sites could be related, in part, to differences in stand density. In uneven-aged, multistoried stands, basal area densities may be similar, but tree spacing and distribution of species and size classes can vary, affecting snow interception, components of solar radiation, and related values for snow evaporation and sublimation losses. The lysimeters within a site represent a variety of stand conditions within the larger density classification, and may give a more representative test of a simulation model.

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Table 2.--Snowpack, runoff and temperature values for the snowmelt lysimeters

Density level	Lys. no.	Lys. runoff	Calculated peak snow WE	Peak snow depth	Days of flow	Aver. daily flow	Degree days to complete melt (max T-42° F)
		inches	inches	inches		inches	
High	97-1	2.58	5.13	16	42	0.0614	77
	97-2	3.73	7.91	26	32	.1166	89
	97-3	1.32	5.16	18	22	.0600	54
Medium	83-1	8.12	8.43	25	48	.2137	165
	83-2	9.39	7.50	28	41	.2290	220
	83-3	13.22	7.11	21	36	.3672	178
Low	95-1	7.74	9.41	34	24	.3225	337
	95-2	5.20	8.29	28	25	.2080	358
	95-3	5.24	7.68	24	29	.1807	337

Although the stand characteristics vary, the lysimeters should respond similarly to the larger environmental influences (e.g., air temperature and solar radiation). Schultz (1973) analyzed lysimeter data in terms of a daily melt ratio: daily melt ÷ total seasonal melt. Using this ratio and an analysis of variance, Thomas Creek melt data showed no differences in mean within each site when a common time period was tested for the high density site or when the total record was tested for the other two sites. The analysis for the high density area was complicated by the fact that lysimeter 97-1 started flowing intermittently on January 28, 32 days before the other units.

Plots of daily melt runoff by day of runoff, beginning January 28, indicated that the lysimeters within each site were synchronized (figure 2A-C). Major peaks and most troughs usually occur on the same day or within a day of each other (e.g., the common peaks of March 22 and March 31 on the low density site).

The plots indicated some conditions which should be explained. For example, the probable reason that lysimeter 97-1 started flow on January 28, was related to its location to the northeast of a small opening (figure 2A). A combination of a relatively low snowpack (table 2) and high incident radiation could have been responsible. Lysimeter 97-3 had a similar snowpack, but was not adjacent to the opening; it started flow on the common date (March 1), but only ran for 22 days, yielding the least water (table 2). Evaporation losses were probably greater during this warmer melt period. The medium density site also started flowing around March 1 (figure 2B); the greater accumulation of snow caused higher volumes and peaks. The high flows of March 18-20 on lysimeter 83-3 have been questioned; the chart and observations on March 20 did not indicate erroneous data, however. We can only guess that extra moisture entered the lysimeter probably from snow dropping from the adjacent tree crowns during an earlier storm. The shape and location of the crowns, with respect to the lysimeter, make this a plausible explanation. This lysimeter also recorded more snowmelt runoff than recorded precipitation, indicating a large redistribution of snow which is a normal occurrence. The low density site accumulated the largest snowpack (least interception) and started melting on March 18 (figure 2C). Conditions were already relatively warm, and melt runoff ended quickly.
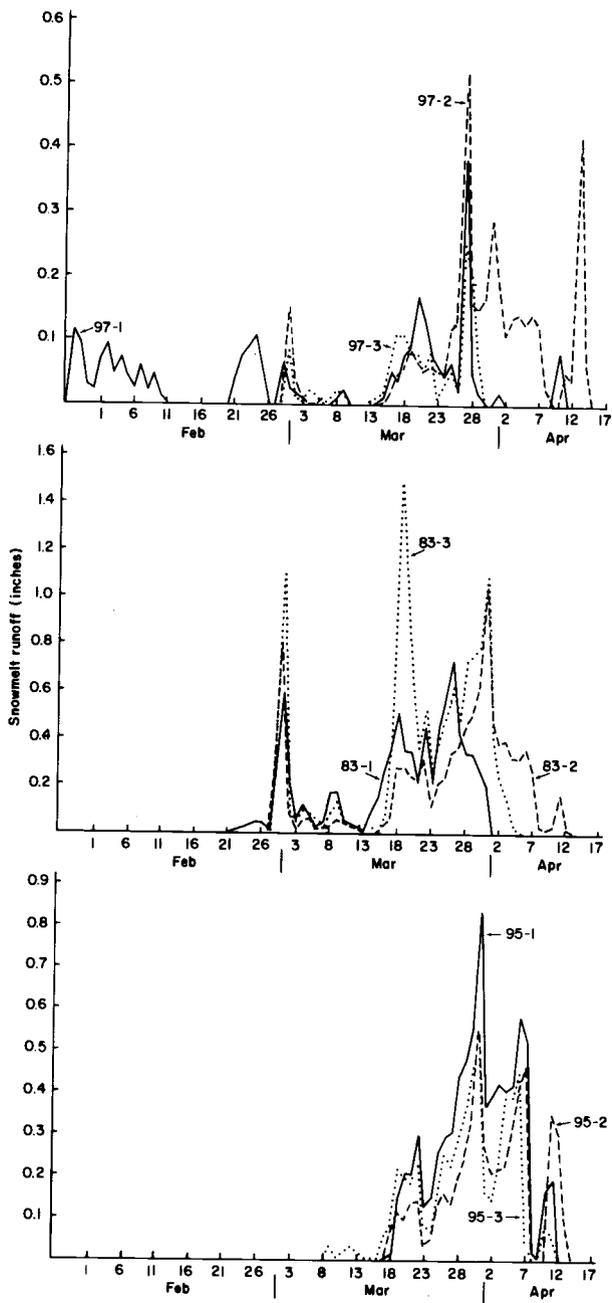
Figure 2.--Daily lysimeter snowmelt runoff for each site was relatively synchronized. Major peaks and troughs occur on the same day or within a day of each other. A = High Stand Density; B = Medium Stand Density; C = Low Stand Density. First flow was recorded on January 28, and last flow on April 14.

Daily temperature data can help explain the fluctuations in runoff (figure 3A). Runoff peaks and troughs corresponded well with fluctuations in temperature. Periods of no flow in mid-February were related to cold weather (daily averages below 20° F).

The relationship between runoff and degree days is well documented (Linsley et al. 1958) and was apparent in this study (figure 3B). Degree days were calculated by subtracting 42° F from the daily maximum temperature. The high density site with its shallower snowpack and higher potential of back radiation from the surrounding canopy required less degree days to start melt or to complete it. The relationships for the other sites were also clear.
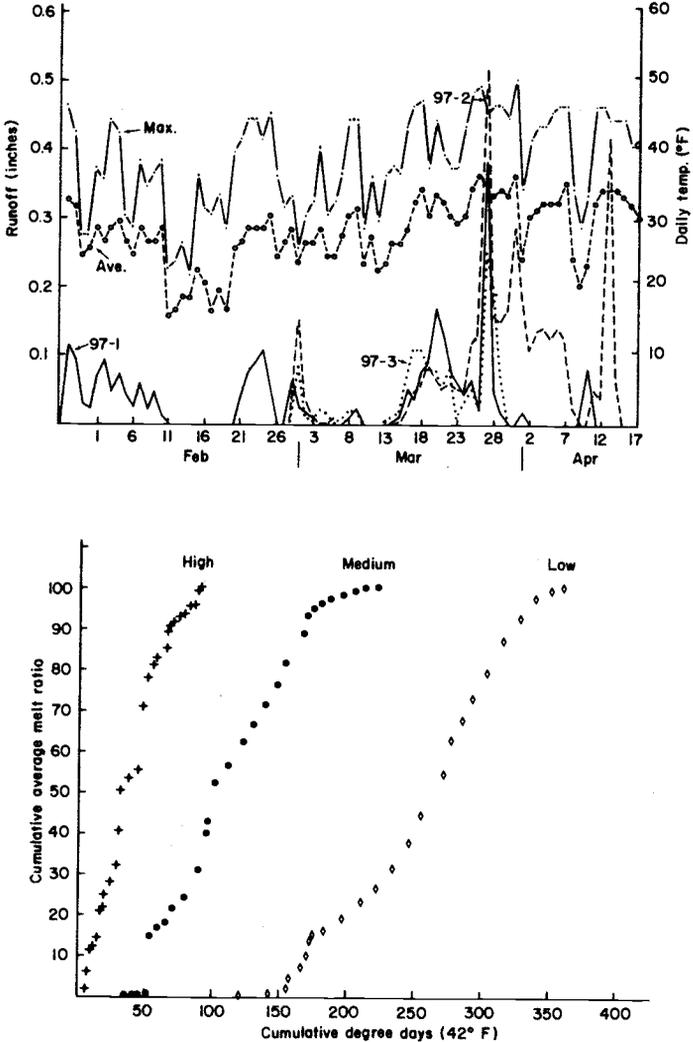
Figure 3.--Snowmelt can be related to fluctuations in air temperature. Runoff peaks and troughs (A) appear related to daily maximum or average temperatures (e.g., the high density site). The three sites (B) varied in the number of degree days required before melt began or ended.

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Haupt (1969) indicates that lysimeter data could be used to predict the timing of peak flow. Our lysimeter snowmelt data from each site were averaged, and the three averages were compared with stream-flow from the North Fork of Thomas Creek. The results showed that the lysimeters appear to be qualita-tively linked to streamflow (figure 4); they usually preceded the stream by 1 or 2 days. The medium density site and high density sites started rising to their first peak on February 27 and 28; Thomas Creek started its first major rise on March 1. All sites showed increases starting around March 16 or 17, with major increases around March 18-20; Thomas Creek started its main rise on March 16. The stream peaked slightly on March 26 before continuing to the high point on April 1; both the medium and low density sites peaked on March 31. The high density site had already passed its peak by this date.
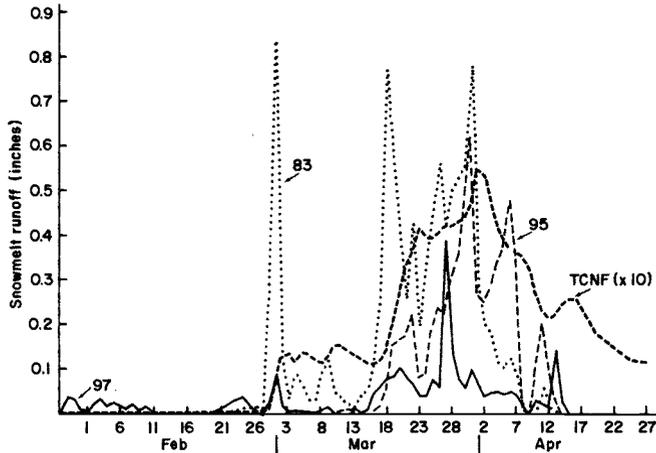

Figure 4.--Changes in average snowmelt from each site were linked to changes in streamflow from the North Fork of Thomas Creek (Thomas Creek values are multiplied by 10 for visual clarity).

WATER BALANCE COMPARISONS

Lysimeters only measure the runoff component of the hydrologic cycle. Reliable measurements of the other main components are necessary before a simulation model evaluation can be conducted. A test will not be valid if poor data are utilized to "drive" a model or if the lysimeters do not represent real environmental conditions. The reliability of the lysimeters and of the associated snowpack and meteorological measurements for each weekly period can be checked by using water balance equations of the form:

LYSRO = (WE1 - WE2) + THRUFAL $\pm$ Error
where:
LYSRO = Lysimeter runoff
WE1 = Calculated snowpack WE at the beginning
WE2 = Calculated snowpack WE at the end
THRUFAL = Throughfall

Throughfall values were derived from the two Thomas Creek recording precipitation gages, adjusted for interception. A standard precipitation gage was installed in an opening in the study area to provide more localized information. Interception data were not available for Arizona mixed conifer forests; we used the ratio of accumulated water equivalent, as measured by a snow tube, at each lysimeter to gage precipitation. Precipitation was further adjusted by a factor of $\pm$1-15% to allow better equality in the equations. This procedure could be justified by the observed variability of snow cover within the mixed conifer forest.

The water balance analysis indicated that the equations did not account for all water losses and gains. All installations had periods of losses and of gains. The lysimeters did not measure all snowpack decreases during warm weather. Such losses occurred on all or most of the 9 units during 6 of the 15 periods. For example, for the period ending April 3 on lysimeter 95-2, the equation would be:

1.97 = (4.83 - 1.16) + 0.12 - 1.82.

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Snow evaporation was the logical explanation for part of the loss, but we did not have quantitative values or ranges for mixed conifer forests. Snow evaporation losses of from 0.006 to 0.016 inch per day have been reported for an Arizona ponderosa pine site (USDA Forest Service 1960). Linsley et al. (1958) assumed a general upper limit of 0.2 inch per day, but this is probably for open sites. Solar radiation measurements, to be collected in the future, should provide a better idea of snow evaporation potential. Another small amount of snow water would go into soil or litter-duff storage; this would occur when early snows fall on dry soils or if the soil is intermittently bare during the winter. Analyses of the forest floor and soil in each lysimeter after the study should help our understanding of this loss. The total seasonal unaccounted losses averaged 7.22 $\pm$ 0.32 inches for the three lysimeters on the high density site, 4.93 $\pm$ 0.46 inches for the medium density site, and 5.78 $\pm$ 0.32 inches for the low density site. However, evaporation and soil moisture recharge could only account for a fraction of the total.

Gains, above the amount for adjusted precipitation, were also calculated. These were less common than the calculated losses and were generally small (58% were less than 0.5 inch). A sample calculation, for the period ending on February 21, for lysimeter 95-3 is:

$$0 = (3.26 - 4.68) + 1.04 + 0.38.$$

Most gains were associated with periods of snowfall and could indicate moisture entering the lysimeters from adjacent tree crowns or because of some wind movement; however, some relatively large gains were not associated with heavy snow accumulations.

One explanation for the losses and gains could be the procedure of calculating lysimeter snowpack WE by multiplying average lysimeter snow depth by a snow tube density. The depth measurements were good, but in 1978, only one tube sample was taken periodically near each lysimeter. Snow density on Thomas Creek can be quite variable, especially in the second half of the season (Ffolliott and Thompson 1977); even a difference of 5% on a deep pack can result in large water equivalent differences. For example, the density difference between 0.36 and 0.34 gm per cm^3 would result in a WE difference of 0.48 inch on a 24-inch snow depth. Even under ideal conditions snow tubes are not extremely accurate, i.e., $\pm$1.2 inches (Schultz 1973). Often ice lenses, near the base of the snowpack, are not picked up by the tube. We attempted to remedy this situation after the 1978 winter, by increasing the number of snow tube measurements made around each lysimeter. Average snowpack values were used in later calculations.

The preliminary water balance analyses also indicated a need for more intensive environmental monitoring and for more research to gain a better understanding of interception and snow evaporation within mixed conifer forests. Intensive snow tube sampling should increase the accuracy of the interception values; a snow evaporation study would be an area for future research.

CONCLUSION

First-year results show that the snowmelt lysimeters worked well within three sites, representing different mixed conifer stand densities, on the North Fork of Thomas Creek watershed, and eventually should be useful in validating various snowmelt simulation models. Although runoff totals varied, daily melt ratios, and runoff timing within each site were relatively synchronized and were related to air temperature data. Average lysimeter runoff timing was related to increases and peaks for the Thomas Creek North Fork stream. Peak flows for the lysimeters usually preceded the stream by 1 or 2 days.

Some mechanical problems were discovered during the evaluation. Moisture freezing in the tubing connecting the lysimeters and their stilling wells caused the loss of the 1977 record. However, this problem was easily corrected by increasing the tubing insulation. The soldered drain joint should be reinforced to prevent failing.

Water balance equations using lysimeter runoff and associated meteorological data were calculated. A valid test of a simulation model requires that the equations be balanced and be representative of the actual environmental processes. The lysimeter runoff values were consistent; however, the analysis did indicate some deficiencies, (e.g., in sampling snow density and the need for more intensive environmental monitoring). Correction of the problems would allow for accurate testing of computer models to simulate snowmelt.

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