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**A Research Report for
Westinghouse Hanford Company**

**Earthquake Recurrence
Rate Estimates for Eastern
Washington and the
Hanford Site**

A. C. Rohay

August 1989

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
Operated for the U.S. Department of Energy
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EARTHQUAKE RECURRENCE RATE ESTIMATES
FOR EASTERN WASHINGTON AND THE
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Richland, Washington 99352

SUMMARY

The historical and instrumental records of earthquakes were used to estimate earthquake recurrence rates for input to a new seismic hazard analysis at the Hanford Site in eastern Washington. Two areas were evaluated, the eastern Washington region and the smaller Yakima Fold Belt, in which the Hanford Site is located.

The completeness of a catalog of earthquakes was evaluated for earthquakes with Modified Mercalli Intensity (MMI) IV through VII. Only one MMI VII earthquake was reported in the last 100 years in eastern Washington. The reporting of MMI VI earthquakes appears to be complete for the last 80 years, and the reporting of MMI V earthquakes appears to be complete for the last 65 years. However, MMI IV earthquakes are consistently under-reported.

For a limited set of earthquakes, both MMI and magnitude (M_L) have been reported. A plot of these data indicated that the Gutenberg-Richter relationship could be used to estimate earthquake magnitudes from intensities.

A recurrence curve for the historical earthquake data was calculated using the maximum likelihood method, including corrections for the width of the magnitude groups that result from the intensity-to-magnitude conversion. The slope of the recurrence curve (i.e., b-value) was found to be -1.15.

Another catalog, one that listed instrumentally detected earthquakes from 1969 to the present, was used to supplement the historical earthquake data. Magnitudes were determined using a coda-length method (M_C) that had been approximately calibrated to local magnitude M_L . For earthquakes whose M_C was between 3 and 5, the b-value ranged from -1.07 to -1.12.

The rates of earthquakes with $M_L \geq 4$ in eastern Washington were normalized to a 100,000-km² area. No significant differences were found between the area-normalized rates of earthquakes calculated from the historical and the instrumental data. Similarly, the area-normalized recurrence rates for the smaller Yakima Fold Belt also were not significantly different from the rate determined for the eastern Washington region.

From this analysis, we conclude that the recurrence relationship

$$\log(N) = \log(0.5) - 1.15 (M_L - 4)$$

where N is the cumulative number of earthquakes in 100,000 km² with magnitudes greater than or equal to M_L is appropriate input for estimating seismic hazards at the Hanford Site.

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DESCRIPTION OF THE HISTORICAL EARTHQUAKE CATALOG

The catalog of earthquakes produced by Woodward-Clyde Consultants (Washington Public Power Supply System 1981, Table 2.5-5; DOE 1988, Table 1.4-2) has been used to develop recurrence rate estimates for eastern Washington and for the Yakima Fold Belt, a subregion of eastern Washington. These regions represent possible choices for characterizing the seismotectonic environment of the Hanford Site.

Figure 1 (from DOE 1988, Figure 1.4-5) shows the locations of every earthquake with either a Modified Mercalli Intensity (MMI) of IV or greater or a magnitude (on any of several scales) greater than 3 that were reported prior to 1969 in the area of eastern Washington. The smaller box shows the area of the Yakima Fold Belt. The Hanford Site is located in the eastern half of the Yakima Fold Belt.

Figure 2 (from DOE 1988, Figure 1.4-6) shows the locations of every earthquake reported since 1969 with a magnitude greater than 3.0 for the same regions. Nearly all of these earthquakes were located by the eastern Washington seismic network that was installed in 1969. Because network coverage has not extended to the eastern and southern boundaries of the region in Figure 2, the area indicated by the larger box represents the area of complete detection by the seismic network at the magnitude 3 level since 1969. The smaller area representing the Yakima Fold Belt is also shown in this figure.

Tables 1 through 4 list the earthquakes for which either the intensity was IV or greater or the magnitude was 4 or greater. Changes and additions to the catalog given by DOE (1988, Table 1.4-2) are listed in Table 5.

Figure 3 plots intensity versus magnitude for the earthquakes in Table 4 and also shows three intensity-magnitude relationships identified from the literature. The Gutenberg-Richter relationship appears to fit the data best, because it fits both the point at magnitude 5.75 (the well-studied 1936 Milton-Freewater earthquake) and the tightly clustered data for intensity V. Although there is greater scatter in the data for intensity VI, the Gutenberg-Richter line appears to fit them at least as well as any of the

FIGURE 1. Historical Seismicity of the Columbia Plateau and Surrounding Areas (from DOE 1988). All earthquakes between 1850 and 1969 with a Modified Mercalli Intensity (MMI) of IV or larger or with a magnitude of 3 or greater are shown. The Yakima Fold Belt is enclosed by the smaller box (118.75°-121.0° W, 45.75°-47.25° N).

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FIGURE 2. Instrumental Seismicity of the Columbia Plateau (from DOE 1988). All earthquakes between 1969 and 1986 with magnitudes greater than 3 are shown. The larger box (117.5°-121.5° W, 45.5°-48.5° N) represents the region covered by the seismic network since 1969. The Yakima Fold Belt is enclosed by the smaller box (118.75°-121.0° W, 45.75°-47.25° N).

TABLE 1. Eastern Washington Earthquakes with Modified Mercalli Intensity (MMI) IV. Events for which a magnitude was also reported are in Table 4. Modifications to catalog may be listed in Table 5.

Date	Time	Latitude	Longitude	Intensity	Remarks
24 NOV 1866	18:10:00.0	45.595N	121.173W	IV	The Dalles, Oreg.
2 SEP 1891	10:30:	47.100N	118.400W	IV	Ritzville
17 SEP 1891	04:30:00.0	44.940N	121.033W	IV	Salem, Oreg.
29 FEB 1892	10:45:00.0	45.595N	121.173W	IV	The Dalles, Oreg.
21 JAN 1909	05:	47.800N	120.000W	IV	Chelan
5 MAR 1915	05:10:00.0	47.830N	120.020W	IV	Lakeside
5 MAR 1915	05:30:00.0	47.830N	120.020W	IV	Lakeside
18 JUL 1915	20:54:00.0	47.830N	120.020W	IV	Lakeside
10 DEC 1915	20:45:00.0	47.672N	117.405W	IV	Spokane
21 FEB 1918		46.867N	121.333W	IV	Bumping Lake
18 APR 1918	21:13:00.0	47.600N	117.400W	IV	White Bluffs Prairie
28 NOV 1920	11:30:00.0	45.700N	121.500W	IV	Hood River, Oreg.
1 JUN 1922	23:30:00.0	47.672N	117.405W	IV	Spokane
6 JAN 1924	13:09:00.0	46.070N	118.328W	IV	Walla Walla
27 MAY 1924	00:19:00.0	46.070N	118.328W	IV	Walla Walla
23 APR 1926	13:56:00.0	46.070N	118.328W	IV	Walla Walla
8 DEC 1931	14:25:00.0	47.830N	120.020W	IV	Lakeside-Chelan Falls
31 MAY 1933	20:20:00.0	47.842N	120.013W	IV	Chelan
31 MAY 1933	20:30:00.0	47.842N	120.013W	IV	Chelan
9 MAR 1934	16:00:00.0	47.830N	120.020W	IV	Lakeside
22 SEP 1934	11:30:	46.998N	120.540W	IV	Ellensburg
22 SEP 1934	17:37:	46.998N	120.540W	IV	Ellensburg
4 OCT 1934	02:26:	46.998N	120.540W	IV	Ellensburg
11 OCT 1934	21:19:	46.998N	120.540W	IV	Ellensburg
29 OCT 1934	18:36:	46.998N	120.540W	IV	Ellensburg
1 NOV 1935	03:35:00.0	47.472N	115.925W	IV	Wallace, Idaho
30 JUL 1936	11:20:00.0	45.935N	118.388W	IV	Freewater, Oreg.
30 JUL 1936	12:00:00.0	45.935N	118.388W	IV	Freewater, Oreg.
30 JUL 1936	12:20:00.0	46.070N	118.328W	IV	Walla Walla
9 FEB 1937	22:20:00.0	46.070N	118.328W	IV	Walla Walla
4 JUN 1937	14:43:00.0	46.070N	118.328W	IV	Walla Walla
11 AUG 1938	18:52:00.0	45.935N	118.388W	IV	Milton, Oreg.
27 OCT 1938	23:10:00.0	45.935N	118.388W	IV	Milton, Oreg.
26 JAN 1939	07:59:00.0	45.700N	118.700W	IV	Milton, Oreg.
24 MAR 1940	03:04:00.0	46.000N	121.200W	IV	Mt. Rainier
12 APR 1941	17:40:00.0	47.648N	120.069W	IV	Waterville
22 SEP 1943	21:50:	47.967N	119.000W	IV	Grand Coulee
2 SEP 1944	01:25:14.0	46.070N	118.328W	IV	Walla Walla
20 SEP 1944	03:00:00.0	44.900N	116.900W	IV	Rockville, Oreg.
25 DEC 1944	13:12:08.8	47.662N	120.223W	IV	Entiat
27 FEB 1945	11:00:00.0	48.480N	121.190W	IV	Winthrop
2 MAR 1945	07:54:59.3	47.662N	120.223W	IV	Entiat
23 SEP 1945	02:40:00.0	46.070N	118.328W	IV	Walla Walla

TABLE 1. (contd)

Date	Time	Latitude	Longitude	Intensity	Remarks
5 FEB 1946	16:12:42.0	47.800N	120.200W	IV	Chelan-Ardenvoir
6 FEB 1946	03:20:00.0	48.527N	121.430W	IV	Marblemount
22 DEC 1947	10:30:00.0	47.662N	120.223W	IV	Entiat
28 AUG 1948	22:25:00.0	47.957N	117.475W	IV	Deer Park
25 OCT 1948	19:50:00.0	47.842N	120.013W	IV	Chelan
20 DEC 1948	16:18:00.0	44.996N	120.215W	IV	Fossil, Oreg.
20 OCT 1949	16:00:00.0	48.500N	120.500W	IV	Lost River
8 MAR 1950	06:25:00.0	47.662N	120.223W	IV	Entiat
25 JUN 1950	23:45:00.0	47.491N	117.575W	IV	Cheney
9 SEP 1952	09:30:00.0	48.698N	116.315W	IV	Bonnors Ferry, Idaho
9 SEP 1952	09:45:00.0	48.698N	116.315W	IV	Bonnors Ferry, Idaho
9 SEP 1953	09:30:00.0	48.698N	116.315W	IV	Bonnors Ferry, Idaho
6 FEB 1955		47.967N	119.000W	IV	Grand Coulee
31 MAY 1955	23:35:00.0	47.680N	116.773W	IV	Coeur d'Alene, Idaho
12 APR 1958	00:00:00.0	47.900N	119.100W	IV	Electric City
21 JAN 1959	07:15:00.0	46.070N	118.328W	IV	Walla Walla
11 JUL 1959	15:	47.600N	119.300W	IV	Deep Lake
9 NOV 1959	21:10:00.0	45.353N	119.550W	IV	Heppner, Oreg.
22 MAY 1961	01:57:51.4	47.600N	120.200W	IV	Entiat
28 JUN 1961	10:22:52.9	47.537N	120.293W	IV	Rocky Reach Dam

TABLE 2. Eastern Washington Earthquakes with Modified Mercalli Intensity (MMI) V. Events for which a magnitude was also reported are in Table 4. Modifications to catalog may be listed in Table 5.

Date	Time	Latitude	Longitude	Intensity	Remarks
15 DEC 1897		47.800N	120.000W	V	Lakeside
18 OCT 1905	23:	47.800N	120.000W	V	Chelan
2 NOV 1906	01:49:00.0	48.500N	117.900W	V	Colville
18 FEB 1907	12:20:	47.842N	120.023W	V	Chelan
24 MAY 1909	22:	47.730N	120.360W	V	Chelan-Leavenworth
5 JUL 1911	08:00:00.0	46.998N	120.540W	V	Ellensburg
14 OCT 1913	23:00:00.0	45.700N	117.100W	V	Seven Devils Region, Oreg.
18 AUG 1915	14:05:00.0	48.500N	121.400W	V	
28 FEB 1918	23:15:00.0	46.500N	120.500W	V	Yakima
12 MAR 1918	03:26:00.0	47.600N	117.000W	V	Rathdrum, Idaho
1 NOV 1918	17:20:00.0	46.858N	119.375W	V	Corfu
7 OCT 1920	02:	47.633N	120.067W	V	Waterville
6 JAN 1924	23:10:00.0	45.800N	118.300W	V	Milton, Weston, Oreg.
17 OCT 1926	02:45:00.0	45.730N	121.483W	V	White Salmon
27 NOV 1926	18:25:	47.500N	116.000W	V	Rathdrum, Idaho
3 SEP 1930	13:00:00.0	47.300N	117.800W	V	Lamont
18 SEP 1934	24:	46.998N	120.540W	V	Ellensburg
26 SEP 1934	16:15:	46.998N	120.540W	V	Ellensburg
26 SEP 1934	16:45:	46.998N	120.540W	V	Ellensburg
26 SEP 1934	21:15:	46.998N	120.540W	V	Ellensburg
19 OCT 1934	23:31:	46.998N	120.540W	V	Ellensburg
1 NOV 1934	07:28:	46.998N	120.540W	V	Ellensburg
2 NOV 1934	15:17:	46.998N	120.540W	V	Ellensburg
9 JUL 1935	22:45:00.0	47.700N	120.000W	V	Chelan Falls
12 OCT 1935	01:03:00.0	47.662N	120.223W	V	Entiat
18 JUL 1936	16:30:00.0	45.933N	118.383W	V	Milton-Freewater, Oreg.
4 AUG 1936	09:19:00.0	45.800N	118.600W	V	Helix, Oreg.
28 AUG 1936	04:39:00.0	45.933N	118.383W	V	Milton-Freewater, Oreg.
23 FEB 1942	14:03:00.0	47.600N	120.200W	V	Wenatchee-Chelan Falls
12 JUN 1942	09:30:00.0	44.900N	117.100W	V	Halfway and Pine, Oreg.
14 OCT 1942	11:30:00.0	48.310N	120.652W	V	Stehekin
31 OCT 1944	11:34:28.7	47.800N	120.600W	V	
4 JAN 1945	02:34:48.7	47.662N	120.223W	V	Entiat
13 JAN 1948	06:55:00.0	47.900N	120.300W	V	Lucerne-Waterville
4 JAN 1951	13:45:00.0	47.700N	120.000W	V	Chelan-Waterville
7 JAN 1951	22:45:00.0	45.900N	119.200W	V	McNary, Oreg.
4 MAR 1952	19:42:00.0	47.672N	117.405W	V	Spokane
23 MAY 1954	13:41:42.0	48.342N	120.137W	V	Twisp
8 JUN 1954	00:16:13.0	47.500N	116.000W	V	Mortaern, C. d'Alene, Idaho
24 FEB 1956	22:00:00.0	47.900N	119.100W	V	Electric City
31 OCT 1961	03:34:29.8	48.400N	120.000W	V	Okanogan

TABLE 3. Eastern Washington Earthquakes with Modified Mercalli Intensity (MMI) VI. Events for which a magnitude was also reported are in Table 4. Modifications to catalog may be listed in Table 5.

Date	Time	Latitude	Longitude	Intensity	Remarks
5 MAR 1892		46.600N	120.500W	VI	North Yakima
5 MAR 1893		45.900N	119.333W	VI	Umatilla, Oreg.
2 JAN 1906		48.700N	117.800W	VI	Stevens County
14 SEP 1921	11:00:00.0	46.100N	118.250W	VI	Dixie-Walla Walla
30 DEC 1926	17:57:00.0	47.700N	120.200W	VI	Chelan-E. Central Wash.
3 JAN 1927	04:58:00.0	47.593N	120.658W	VI	Leavenworth
24 APR 1943	00:10:46.0	47.300N	120.600W	VI	Leavenworth

TABLE 4. Eastern Washington Earthquakes with Magnitudes Greater than 4 Reported. (Includes events for which intensity could also be found.) Modifications to catalog may be listed in Table 5.

Date	Time	Latitude	Longitude	Intensity(a)	Remarks
28 NOV 1925	01:25:00.0	47.500N	116.000W	V* 4.30ML	
16 JUL 1936	07:07:49.0	46.208N	118.233W	VII 5.75ML	Milton Freewater, Oreg.
7 APR 1941	09:25:00.0	48.300N	119.600W	VI 5.00ML	
1 NOV 1942	18:50:06.0	48.000N	116.700W	VI 5.50ML	Sandpoint, Idaho
15 MAR 1949	20:53:11.0	45.500N	117.000W	VI* 4.80ML	
1 NOV 1957	10:12:02.0	46.700N	121.500W	V 4.20ML	
18 DEC 1957	23:25:00.0	47.500N	116.000W	VI 5.00ML	
12 APR 1958	22:37:11.0	48.000N	120.000W	VI 4.10ML	
6 AUG 1959	03:44:32.0	47.800N	119.900W	VI 4.40ML	Chelan
31 OCT 1961	02:35:00.0	48.400N	120.000W	V 4.30ML	
15 JAN 1962	05:29:00.0	47.800N	120.200W	V 4.30ML	
22 DEC 1963	02:54:04.9	48.590N	119.760W	V 4.40MB	
7 NOV 1965	16:41:47.4	44.900N	117.000W	V* 4.30MB	
28 APR 1965	19:00:00.0	48.600N	116.900W	V 4.30ML	
23 JUL 1966	01:57:08.8	47.200N	119.500W	V* 4.30ML	
30 DEC 1966	03:51:40.3	44.900N	117.000W	V* 4.20MB	
23 NOV 1971	02:12:14.5	48.269N	121.182W	4.10ML	
20 DEC 1973	01:08:28.2	46.868N	119.353W	V 4.38MC	Royal Slope
13 APR 1976	00:47:17.1	45.221N	120.771W	VI 4.80ML	Deschutes Valley, Oreg.
17 APR 1976	02:11:44.4	45.080N	120.797W	4.20ML	Deschutes Valley, Oreg.
19 JAN 1979	14:55:15.4	47.923N	119.685W	V 3.60ML	Chief Joseph Dam
8 APR 1979	07:29:37.8	45.995N	118.447W	4.15MC	Walla Walla

(a) Pre-1969 intensities indicated by * are estimated in Table 5.

TABLE 5. Modifications to the Washington Public Power Supply System's (1981) Earthquake Catalog

INTENSITIES ADDED:

BASED ON CATALOG WITH MULTIPLE SOURCE ENTRIES

1 NOV 1957 (V)	18 DEC 1957 (VI)	12 APR 1958 (VI)
6 AUG 1959 (VI)	31 OCT 1961 (V)	15 JAN 1962 (V)
28 APR 1965 (V)		

INTENSITIES, MAGNITUDES ADDED AND CHANGED:

BASED ON CATALOG AND NRC REVIEWS (NRC 1982)

1 NOV 1918 CORFU AND 20 DEC 1973 INTENSITIES BOTH V
16 JUL 1936 MILTON FREEWATER MS= M_L =5.75

LOCAL MAGNITUDE (M_L) USED WHENEVER AVAILABLE:

7 APR 1941 M_L =5.00	23 JUL 1966 M_L =4.30
23 NOV 1971 M_L =4.10	13 APR 1976 M_L =4.80
17 APR 1976 M_L =4.20	

INTENSITIES ESTIMATED FROM MAGNITUDES FOR PRE-1969 EVENTS:

(SEE FIGURE 3)

(INDICATED BY * IN TABLE 4)

28 NOV 1925 M_L =4.30	V*	15 MAR 1949 M_L =4.8	VI*
7 NOV 1965 M_B =4.30	V*		
23 JUL 1966 M_L =4.30	V*		
30 DEC 1966 M_B =4.20	V*

FIGURE 3. Relationship Between the Maximum Observed Modified Mercalli Intensity (MMI) and Richter Magnitude (M_L). All available intensity-magnitude pairs for eastern Washington are shown. Previously published intensity-magnitude relationships shown are 1) $M_L = 1 + 2/3 \text{ MMI}$ (Gutenberg and Richter 1956), 2) $M_L = 2.1 + 0.5 \text{ MMI}$ (Krinitzky and Chang 1975), 3) $M_L = 1.85 + 0.49 \text{ MMI}$ (Toppozada 1975). The Gutenberg-Richter relationship is chosen based on the fit at intensities V and VII.

other lines do. Therefore, the Gutenberg-Richter relationship was selected and used 1) to estimate intensities from magnitudes for all earthquakes that occurred before 1969 (see Tables 4 and 5) and then 2) to estimate the magnitude recurrence from the intensities.

EVALUATION OF THE HISTORICAL EARTHQUAKE CATALOG

Counts of the number of earthquakes for each intensity are shown in Figure 4 in 5-year increments and also grouped into overlapping 15-year periods. Figure 5 plots the number of earthquakes per year in each of these 15-year periods. It appears that there are too few intensity IV earthquakes to be considered representative of the true number (in general, we expect approximately five times as many intensity IV earthquakes as intensity V earthquakes). Therefore, examining the intensity IV earthquakes would be unlikely to produce reasonable, representative results.

The length over which the record is complete for intensity V and VI earthquakes was estimated using Figures 4 and 5. The figures show an apparent increase in the number of intensity V earthquakes from around 1930 to 1940. This increase reflects a 1934 sequence of earthquakes near Ellensburg and aftershocks of the intensity VII Milton-Freewater earthquake in 1936. In Figure 4, it appears that the number of intensity V earthquakes in the 15-year period beginning in 1905 is about the same as in any of the five overlapping periods that began after 1935. In contrast, the number of intensity VI earthquakes appears to be low before about 1920. Because intensity VI earthquakes are more likely to be reported, the complete record would be expected to be longer for the intensity VI earthquakes than for the intensity V earthquakes. It is possible that the lower rate of intensity VI earthquakes prior to 1920 was a real phenomenon and not an artifact of reporting, considering that two intensity VI earthquakes were reported before 1900.

The total numbers and annual rates of intensity V and VI earthquakes per year are tabulated in Table 6, averaged over 50- to 80-year periods that end in 1970 (no intensity V earthquakes occurred in 1969 or 1970). The standard error is computed as the square root of the number of earthquakes divided by

	1885	1900			1915			1930			1945			1960			1970
		3			1		6	4	1	9	9	6	10	5	6	2	
		3			1		11			24		21					
MMI=			3			7			14			25			13		
IV				1			10			19			21			8	
			1		4	2	4	2	3	8	5	4	2	5	2	4	4
		1			6			9		17			9				
MMI=			1			10			13			11			11		
V					5		8			16			11			10	
		2			1			1	2			3	1		3		
		2			1			3		3			4				
MMI=			2			1			3			4			3		
VI				1			1			2			4			3	

FIGURE 4. Number of Earthquakes in 5- and 15-Year Periods in Eastern Washington. The earthquakes in the three Modified Mercalli Intensity (MMI) groups are listed in Tables 1 through 4.

the length of the period. These annual rates can be compared to the 15-year-average rates plotted in Figure 5. The rates of intensity V earthquakes decrease significantly for periods longer than 65 years, the previously estimated period of complete reporting. Different estimates of the rate of intensity VI earthquakes vary much less in proportion to the associated standard errors. Therefore, it appears that the record of intensity VI earthquakes may, in fact, be complete for 80 years without significantly changing the average rate.

Stepp's (1972) method to determine the completeness of the record was used, as shown in Figure 6. The relationship between the standard errors estimated from the square root formula is a function of the length of the

FIGURE 5. Fifteen-Year-Average Annual Rates (n/yr) of Earthquake Occurrence in Eastern Washington ($206,660 \text{ km}^2$). Modified Mercalli Intensity IV (circles), V (squares), and VI (triangles) are shown. Points are plotted at the center of each 15-year interval. Open squares result from removing three MMI V aftershocks of the 1936 MMI VII Milton-Freewater earthquake.

TABLE 6. Historical Earthquake Recurrence Rates (Area 206,660 km²)

Years before 1970 (T)	MMI = V			MMI = VI			MMI = VII		
	n	n/yr	std. err.(a)	n	n/yr	std. err.(a)	n	n/yr	std. err.(b)
50	39	0.78	0.12	10	0.20	0.06			
55	43	0.78	0.12	10	0.18	0.06			
60	45	0.75	0.11	10	0.17	0.05			
65	49	0.75	0.11	11	0.17	0.05			
70	49	0.70	0.10	11	0.16	0.05			
75	50	0.67	0.09	11	0.15	0.05			
80	50	0.62	0.09	13	0.16	0.04			
100							1	0.01	

(a) Standard error is estimated from the $n^{-1/2}$ relationship, approximately valid for $n > 10$.

(b) Standard error is based on Weichert (1980, Figure 1) for $n = 1$; the 68% confidence bounds are factors of 3.3 and 0.2 of the average rate.

time periods. The rates of earthquake occurrence and the standard errors of these rates can be obtained from this plot by fitting lines with a slope of $-1/2$ to the log-log plot. The recurrence rates from variable-length periods should lie on a line with a slope of $-1/2$ if the actual rate is a constant. Data from short periods will be scattered about the lines because a smaller number of earthquakes are included. For long periods, the rates begin to fall below the lines, indicating the effect of incomplete reporting in the early years. Figure 6, like Figure 4, suggests that the complete record for intensity V earthquakes is (uncharacteristically) longer than that for the intensity VI earthquakes.

HISTORICAL EARTHQUAKE RECURRENCE RATES

Annual rates of intensity V and VI earthquakes were calculated for the 60- or 65-year period prior to 1970 (either period gives approximately the same rates). This assumes that both records are complete back to 1905 or 1910. Although these estimates are slightly lower than they would be if estimated for a 50- or 55-year period, the record of intensity V earthquakes does appear to be complete for 65 years. It does not seem reasonable to assume a shorter

FIGURE 6. Estimating the Completeness of the Historical Earthquake Catalog. This method (Stepp 1972) is an alternative to that used in Figure 5 for estimating the completeness of the catalog as a function of time. The standard error of the annual recurrence rate (σ_λ) is given by $N^{-0.5}/T$, where N is the total number of events in T years. The standard error should decrease as $T^{-0.5}$ on the log-log plot if the annual recurrence rate (λ) is constant. The recurrence rates were measured by fitting lines with a slope of $-1/2$ to the points for Modified Mercalli Intensity V (squares) and VI (triangles). The earthquake catalog may be incomplete in the earliest years, as indicated by the vertical arrows (the points progressively fall below the lines for larger T). These periods could be used to obtain the smallest error (σ_λ) in the recurrence rate of earthquakes.

period for the intensity VI data; in fact, a longer period (80 years) gives only a slightly different rate. Because only one intensity VII earthquake has occurred in the region since 1885 (when intensity IV, V, and VI earthquakes were first reported), the rate of intensity VII earthquakes is estimated to be 1 in 100 years, or 0.01.

Table 7 gives incremental and cumulative recurrence rate estimates (n/yr and N/yr, respectively) for the eastern Washington area (Figure 1) and normalizes the cumulative rates to a 100,000-km² area. Cumulative recurrence rates are the sum of recurrence rates for all intensities (or magnitudes) equal to or greater than the given intensity (or magnitude).

The standard errors for the cumulative rates (N/yr) are determined from $N^{0.5}/T$ where $T = 65$ years (the period of completeness). Because the period of completeness for intensity VII was assumed to be 100 years instead of 65 years, 0.65 was added to the cumulative numbers of earthquakes for calculating the standard errors. The equivalent confidence interval for intensity VII is unchanged from the incremental standard errors given above (3.3 and 0.2 times the mean rate).

RECURRENCE CURVES

Figure 7 plots the cumulative recurrence rates per 100,000 km² for the data described above. This plot uses the Gutenberg-Richter intensity-magnitude relationship (Figure 3). The data points at intensity V and VI imply a slope (the b-value) of -1.07, although this value must be corrected for the width of the magnitude groups used in plotting the data.

TABLE 7. Cumulative Recurrence Rates for Eastern Washington

<u>Intensity (MMI)</u>	<u>Incremental Rate (n/yr)</u>	<u>Cumulative Rate (N/yr)</u>	<u>Area-normalized N/yr/100,000 km²</u>
V	0.75 ± 0.11	0.93 ± 0.12	0.45 ± 0.06
VI	0.17 ± 0.05	0.18 ± 0.05	0.087 ± 0.03
VII	0.01	0.01	0.005

FIGURE 7. Historical Earthquake Recurrence Rates Normalized to 100,000 km². Cumulative recurrence rates for eastern Washington (squares) are shown with their standard errors. The slope (b-value) of the line, fitted to the points at MMI V and VI, is -1.07. The one MMI VII earthquake has a known magnitude of 5.75 ± 0.2 . Cumulative recurrence rates for the entire Yakima Fold Belt (solid triangles) and for the eastern half of the Yakima Fold Belt (open triangles) are not significantly different from the rate for eastern Washington.

Sources of uncertainty in the b-value include 1) the intensity-magnitude relationship, 2) the length of the complete catalog, and 3) whether after-shocks should or should not be removed from the catalog. The largest uncertainty is caused by scatter in the relationship between intensity and magnitude. The recurrence rates for intensities V and VI decrease slightly for periods from 55 and 75 years. Removal of aftershocks (if appropriate) would slightly reduce the rate of intensity V earthquakes and would tend to increase the b-value.

Recurrence rate data (Table 8) for the Yakima Fold Belt are also plotted in Figure 7. For this smaller region, it was assumed that the catalog was complete from 1888 to 1989, a 100-year period that includes two intensity VI earthquakes and thirteen intensity V earthquakes. This period was chosen somewhat differently than the period for eastern Washington, so that the two intensity VI earthquakes in 1892 and 1893 would be included. The period was also extended to the present to include the 1973 intensity V earthquake. The

TABLE 8. Earthquakes with Intensities of V or Larger in the Yakima Fold Belt (from Tables 2, 3, 4)

Date	Time	Latitude	Longitude	Intensity(a)	Remarks(b)
5 MAR 1892		46.600N	120.500W	VI	North Yakima
5 MAR 1893		45.900N	119.333W	VI	Umatilla, Oreg. #
5 JUL 1911	08:00:00.0	46.998N	120.540W	V	Ellensburg
28 FEB 1918	23:15:00.0	46.500N	120.500W	V	Yakima
1 NOV 1918	17:20:00.0	46.858N	119.375W	V	Corfu #
18 SEP 1934	24:	46.998N	120.540W	V	Ellensburg
26 SEP 1934	16:15:	46.998N	120.540W	V	Ellensburg
26 SEP 1934	16:45:	46.998N	120.540W	V	Ellensburg
26 SEP 1934	21:15:	46.998N	120.540W	V	Ellensburg
19 OCT 1934	23:31:	46.998N	120.540W	V	Ellensburg
1 NOV 1934	07:28:	46.998N	120.540W	V	Ellensburg
2 NOV 1934	15:17:	46.998N	120.540W	V	Ellensburg
7 JAN 1951	22:45:00.0	45.900N	119.200W	V	McNary, Oreg. #
23 JUL 1966	01:57:08.8	47.200N	119.500W	V* 4.30ML	#
20 DEC 1973	01:08:28.2	46.868N	119.353W	V 4.38MC	Royal Slope #

(a) Intensities estimated from magnitude are indicated by *.

(b) Earthquakes that occurred in the east half of the Yakima Fold Belt are indicated by a #.

rate of intensity V earthquakes is difficult to estimate because seven intensity V earthquakes were clustered at Ellensburg in 1934. Figure 7 also shows recurrence data for earthquakes in just the eastern half of the Yakima Fold Belt. The rate (per unit area) of intensity V earthquakes is slightly lower in the eastern half but the rate of intensity VI earthquakes is unchanged relative to the entire Yakima Fold Belt.

On the basis of these analyses, it was concluded that the earthquake recurrence rate chosen to represent the Hanford Site (in the eastern half of the Yakima Fold Belt) cannot be distinguished from the rate estimated from the entire eastern Washington area. The two assumptions, 1) that the recurrence rate is uniform throughout the Yakima Fold Belt and 2) that the recurrence rates in the east and west halves of the Yakima Fold Belt are different, give recurrence rates that are higher and lower, respectively, than the recurrence rate for eastern Washington. Therefore, if these two assumptions are equally weighted, the eastern Washington recurrence rate provides a reasonable average. The differences in recurrence rates between the Yakima Fold Belt and eastern Washington are comparable to the standard error of the eastern Washington recurrence rates and are much smaller than the standard errors of the small-area estimates.

CORRECTION FOR WIDTH OF MAGNITUDE GROUPS

Utsu (1966), Weichert (1980), and Bender (1983) have given formulas for data grouped into equal-width magnitude ranges. Utsu's formula for determining the b-value is

$$b = \frac{1}{d \ln(10)} \tanh^{-1} \frac{d}{M_{ave} - M_{min}} \quad (1)$$

where d is the width of the magnitude groups (equal to 0.67 as calculated from the Gutenberg-Richter relationship), M_{ave} is the average magnitude of

the earthquakes, and $M_{\min}$ is the minimum magnitude of the lowest group (magnitude 4.0 in this case). Using this formula results in a corrected b-value of -1.15.

A method of replotting the recurrence data was developed that reproduces this correction exactly, properly adjusts the fitted line downward, and does not depend on equal-width magnitude ranges. The first step involves assuming that half of the earthquakes are larger than the center of each magnitude range. In a cumulative recurrence curve, then, half of the earthquakes for a given range should be added to the total number of earthquakes in all larger-magnitude ranges and replotted below the center point (Figure 8). This approach would be correct if this point represented the median magnitude of each intensity group.

For the few observations available here that can be used to estimate an intensity-magnitude relationship, the Gutenberg-Richter relationship appears to predict the median magnitude for intensity V and VI (see Figure 3) fairly well. Using this assumption, the b-value is estimated from points replotted below the center of the range. The b-value determined, -1.15, agrees exactly with the slope predicted by the Utsu relationship.

Correcting for the magnitude grouping depends on whether the values predicted by the intensity-magnitude relationship represent the median, the mean, or some other estimate of the distribution of magnitudes for that intensity. This distribution was estimated from a small subset of the data because the distribution of the whole data set is unknown. If the data within each group were distributed exponentially with the same b-value as the whole data set, there would be more earthquakes in the lower half than in the higher half of the range.

The second step in replotting is to estimate for the whole data set where the median magnitude value is located within each intensity group, assuming that the magnitude distribution within each group is exponential. The b-value determined in the first step is used to estimate how far the point should be offset to the left to account for the more frequent

FIGURE 8. Correction of Historical Earthquake Recurrence Rates for Magnitude Grouping. All symbols are the same as in Figure 7, except for correction to the lower limit of each magnitude range (open squares). The corrections reflect the assumption that centers of intervals represent the median value of the groups (open circles) and the assumption that distribution within the groups is exponential with a b -value of -1.15 (solid circles).

occurrence of earthquakes in the left half of the magnitude range. The position within the range x (above the lower limit) is calculated from

$$1 - 10^{-bx} = (0.5)(1 - 10^{-bd}). \quad (2)$$

This point represents the median of a magnitude group whose distribution is governed by the b -value.

The value determined for $d = 0.67$ and $b = -1.15$ is $x = 0.202$ (compared to 0.333 for the center of the range), and this correction is shown in Figure 8. This step moves the points an equal amount to the left and does not affect the b -value because, in this case, the magnitude distributions have been assumed to be the same for each intensity group. If each intensity group had a different magnitude distribution, the median value would be offset a different amount from the center for each group, and a small adjustment to the b -value would result. Such adjustments lead to an iterative process of updating the exponential magnitude distribution within groups according to the distribution of the whole data set.

Because of the uncertainty in estimating the median magnitude within each of the intensity groups, two alternative recurrence relationships are shown in Figure 8. The upper line corresponds to the assumption that the Gutenberg-Richter relationship predicts the median magnitude in each group. The lower line corresponds to the assumption that the earthquakes within each group are distributed exponentially and that the median magnitude is smaller than the central value of the range. These two alternative relationships predict that the average recurrence rate (in 100,000 km²) for magnitudes ≥ 4 is 0.45/yr to 0.65/yr.

RECURRENCE RATE FOR INSTRUMENTAL MAGNITUDE DATA

Since 1969, the eastern Washington seismic network has provided a catalog of earthquakes with a magnitude precision of 0.1 units. However, magnitude accuracy is probably only about 0.2 to 0.3 units. The post-1969 earthquakes larger than coda-length magnitude 3.0 have been listed by DOE (1988, Table 1.4-2). The numbers of earthquakes in each magnitude group for the

regions shown in Figure 2 are plotted in Figure 9. The catalog of earthquakes with magnitudes below 4.0 may be incomplete in the Idaho, Oregon, and northeastern Washington portions of Figure 2. Such incompleteness would explain why the area-normalized recurrence rate for small earthquakes in the large region shown in Figure 2 is significantly lower than the rate for the smaller eastern Washington area.

The instrumental recurrence rates for eastern Washington and the Yakima Fold Belt are similar to the rates determined from the historical data. High b-values are consistently indicated, and the rates of earthquakes greater than magnitude 4 are comparable. The apparent agreement between the historical and instrumental earthquake recurrence rates depends on the relationship between local magnitude (M_L) and coda-length magnitude (M_C). The NRC (1982) has suggested that M_C is larger than M_L by 0.3 units. However, the original investigators of the M_C - M_L relationship (UWGP 1979) indicated that no correction to M_C was substantiated because of the large scatter in the data. The NRC's M_C - M_L comparison was made only for earthquakes smaller than magnitude 4 and so may not be applicable above magnitude 4. Both the M_C - M_L and the MMI - M_L relationships have such large uncertainties (on the order of 0.3 units) that the apparently precise agreement between the instrumental and historical recurrence rates in eastern Washington may be merely coincidence.

CONCLUSION

In summary, this analysis has determined the following cumulative annual recurrence rates (normalized to an area of 100,000 km²) for earthquakes greater than magnitude 4:

<u>Data</u>	<u>N</u>	<u>b-value</u>
Instrumental Data		
Eastern Washington	0.45	-1.07
Yakima Fold Belt	0.60	-1.12
Historical Data		
Eastern Washington	0.45	-1.15
Yakima Fold Belt	0.52	
East half Yakima Fold Belt	0.35

FIGURE 9. Earthquake Recurrence Curves, 1969-1986. Cumulative annual recurrence rates are based on coda-length magnitudes (M_C) for three regions, normalized to a 100,000-km² area: Yakima Fold Belt (triangles), eastern Washington (filled circles), and eastern Washington and Oregon and northern Idaho (open circles). The slopes (b-values) determined using the maximum likelihood method are shown at lower right. See Table 9.

TABLE 9. Recurrence Data from the Eastern Washington Regional Seismic Network Catalog, April 1969 Through October 1986 (17.5 Years)^(a)

Eastern Washington, Oregon, and Northern Idaho				Eastern Washington				Yakima Fold Belt			
M(b)	n(c)	N(d)	N/yr	M	n	N	N/yr	M	n	N	N/yr
3.0	19	94	2.60	3.0	19	90	5.10	3.0	6	41	8.15
3.1	12	75	2.07	3.1	12	71	4.02	3.1	8	35	6.96
3.2	17	63	1.74	3.2	17	59	3.34	3.2	7	27	5.37
3.3	12	46	1.27	3.3	12	42	2.38	3.3	6	20	3.98
3.4	7	34	0.940	3.4	7	30	1.70	3.4	4	14	2.78
3.5	3	27	0.747	3.5	2	23	1.30	3.5	1	10	1.99
3.6	3	24	0.664	3.6	3	21	1.20	3.6	1	9	1.79
3.7	2	21	0.581	3.7	2	18	1.02	3.7	1	8	1.59
3.8	6	19	0.525	3.8	6	16	0.906	3.8	4	7	1.39
3.9	2	13	0.360	3.9	2	10	0.566	3.9		3	0.597
4.0	2	11	0.304	4.0	1	8	0.453	4.0	1	3	0.597
4.1	1	9	0.249	4.1	1	7	0.396	4.1		2	0.398
4.2	3	8	0.221	4.2	2	6	0.340	4.2	1	2	0.398
4.3	1	5	0.138	4.3	1	4	0.227	4.3		1	0.199
4.4	1	4	0.111	4.4	1	3	0.170	4.4	1	1	0.199
4.5		3	0.0830	4.5		2	0.113	4.5			
4.6	1	3	0.0830	4.6	1	2	0.113	4.6			
4.7		2	0.0553	4.7		1	0.0566	4.7			
4.8	1	2	0.0553	4.8		1	0.0566	4.8			
4.9		1	0.0277	4.9		1	0.0566	4.9			
5.0	1	1	0.0277	5.0	1	1	0.0566	5.0			

Areas (see Figure 2):

115.5-121.5W	454 km	117.5-121.5W	303 km	118.75-121.00W	167 km
44.9- 49.0N	455 km	45.5- 48.5N	333 km	45.75- 47.25N	172 km
	206,570 km ²		100,899 km ²		28,724 km ²

Average Magnitudes and b-Values

3.3947	3.3622	3.3463
b=0.99	b=1.07	b=1.12

- (a) Magnitudes in this catalog earlier than July 1971 should be corrected downward by 0.3 units (UWGP 1986). For the eastern Washington b-value calculation, this reduced the b-value from 1.07 to 1.04, which is not considered to be significant.
- (b) M = magnitude (determined by coda-length method).
- (c) n = number of earthquakes with magnitude M.
- (d) N = number of earthquakes with magnitude $\geq M$.

From this analysis, we conclude that the recurrence relationship

$$\log(N) = \log(0.5) - 1.15 (M_L - 4) \quad (3)$$

where N is the cumulative number of earthquakes with magnitudes greater than or equal to M_L in 100,000 km², is appropriate input for estimating seismic hazards at the Hanford Site.

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