SNAP 8 POST-SHUTDOWN GAMMA RADIATION APPROXIMATIONS

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An evaluation was made of an approximate method for calculating the dose rate resulting from fission product gamma radiation after reactor shutdown. Safety analyses for advanced nuclear missions in space have used this technique for determining radiologically safe operations. This method assumes that the dose rate $D_1(r, t)$, received from a shutdown reactor is directly proportional to the residual gamma power level at that time.

To check the validity of this "power ratio" assumption, energy-dependent detector responses were calculated for normalized sources in the Perkins and King energy group structure for a SNAP 8 power system on a NASA space station. Gamma decay rates were then calculated by using an expanded, updated list of isotopic decay data, and from these, actual detector responses $D_2(r, t)$ were found for the SNAP 8 system. The two detector responses, D_1 and D_2, were then compared at several times after shutdown and at detector positions around the space station. An error of several thousand percent was found for many detectors at times greater than one year; it was also found that an increase in material attenuation produced an increase in error and that energy-dependent detector response, such as dose rates, showed greater discrepancy between D_1 and D_2 than did the energy flux.

It was concluded that these discrepancies were caused by a decrease in the proportion of high-energy gammas released at longer shutdown times. This softening of the decay gamma spectrum with time caused an increased attenuation of decay gamma energy; invalidating the power ratio assumption. Because of the complexity of the space station geometry, these conclusions were checked and verified by a point source in infinite water calculation. The results indicate that energy-dependent calculations must be made to determine decay gamma dose rates for actual reactor configurations. A simplified method for making these calculations has been devised.

This paper summarizes the results from the determination of the nuclear environment produced by the SNAP-8 reactor on the space station. The study was concerned with determination of the gamma radiation environment produced by the reactor in its shutdown mode, and its variation with respect to time elapsed after shutdown.

The general approach to this and similar shutdown reactor radiation problems, which has been in use prior to this study, involves two steps. The first step is to research the available literature and obtain data, generally in graphical form, which gives the ratio of residual shutdown gamma power to operating power, versus the two parameters of reactor operating time prior to shutdown and the time elapsed after shutdown at which one is interested in determining the radiation environment. The second step is to assume that the gamma dose rate is directly proportional to the residual gamma power level, determine the constant of proportionality, and use it to determine the gamma dose rate from the residual gamma power level found in the first step.

The accuracy of this approach depends on the accuracy of the graphs from which the gamma power ratio is found and the reliability of the assumption that the gamma dose rate is directly proportional to the residual gamma power level. Both of these matters were investigated. The investigation has yielded new power ratio curves which incorporate more recent isotopic data than had been used previously, a determination of the problems encountered, and the error incurred in relating gamma dose rate directly to residual gamma power, plus a simplified method of performing these calculations in the future.

In addition, a radiation transport analysis was made of the nuclear power system for the space station, using the Point Kernel technique to determine the radiation attenuation characteristics of the space station. The results of this portion of the study show the relative magnitude of the geometric and material attenuation, by energy group, of gamma radiation in and around the nuclear-powered space station. These results will be very useful in later investigations in that the gamma radiation environment at any of the detector positions may be quickly found for a U-235 reactor by "de-normalizing" them. i.e., by multiplying the normalized detector response in each energy group by the ratio of the actual source in that group to the source used in the normalized calculation. This process is applicable to future analysis of a U-235 reactor at any power level in both the operating and post-shutdown phases.

REVISION OF POST-SHUTDOWN POWER VERSUS TIME DATA

The General Dynamics data on post-shutdown gamma power as a function of reactor operating time and time elapsed after shutdown (ref. 1) has proven to be a very helpful tool in performing radiation analyses on SNAP-type nuclear power systems. The original information was compiled for a NERVA-type nuclear propulsion reactor, but if the same reactor fuel is used (U-235), the data may be applied to any nuclear system. There are a few disadvantages in using this material; first, it is based on fission product data which was compiled in 1958 and 1959, and, second, the graphs contain information for reactor operating times only up to 10^4 seconds (approximately 3 hours). It was felt that a major improvement could be made to the post-shutdown gamma power data if these data were updated to include the latest fission product decay information and if results for longer reactor operating periods were incorporated. References 2 and 3 list the data in use up to 1963, with reference 3 having the more recent information, including the fission product data for 125 nuclides.

Burrell and Watts (ref. 4) supplied more up-to-date fission product data, which included a library of decay data for 200 nuclides, plus a computer program for utilizing the data. Modifications were made to the code, and an output plotting technique was written and added to it. Figure 1 shows the results of the calculation with this code in the form of total shutdown gamma power versus time after shutdown and operating time. Operating times from 1 to 1×10^9 seconds (approximately 30 years) were included in the calculations. The time after shutdown began at 1×10^2 seconds, since this was the minimum that could be used from the basic input data without extrapolation, and it was felt that periods of time shorter than this were not of interest at present.

Figures 2 through 8 display similar data, but in this case, separately for the seven Perkins and King energy groups. By presenting the data in this format, with a separate graph for each energy group rather than for each reactor operating time, the effect of operating time and shutdown time is more apparent. In this form, the results are more applicable to future calculations, as described in the next section.

EVALUATION OF POST SHUTDOWN DOSE APPROXIMATIONS

An evaluation was made of an assumption used in earlier radiation environment studies of reactors for nuclear missions. This assumption is that the dose rate received from a shutdown reactor is directly proportional to the residual gamma power level. For example, at a given time after the reactor has been shut down when the decay gamma power level is $P(t_1)$ watts, a calculation determines the dose rate at a detector to be $D_1(r, t_1)$ rads. Then, at any other time after shutdown when the decay gamma power level is $P(t_2)$ watts, the dose rate at the same detector can be found from the simple equation

$$D_1(r, t_2) = \frac{D_1(r, t_1)}{P(t_1)} P(t_2)$$

Note that the ratio of dose rate to residual power level at t becomes the constant of proportionality by which the new residual power level is multiplied. The obvious advantage of this technique for calculating decay gamma dose rates is its simplicity. Only one transport calculation need be performed; it can then be scaled to apply to any time after shutdown.

The following approach was used to check the validity of this "power ratio" assumption. As with the original assumption, only one transport calculation was made for each detector point; however, the desired information from this calculation was the dose rate as a function of energy. In particular, the doses, D_i, received from a unit source (1 MeV/sec) in each of the seven Perkins and King energy groups were calculated. Then, using the revised gamma energy release data, Γ_i, as described in the previous section, the dose at detector point r and at time t was calculated by

$$D_2(r, t) = \sum_{i=1}^{7} \Gamma_i(t)\, D_i(r) ,$$

where the summation is over the seven Perkins and King energy groups.

The doses calculated, D_1 and D_2, were then compared for several times and detector points around the space station. The discrepancy between doses seemed to depend on three different factors: time, position, and type of response. First, the error between the two methods increased greatly with increasing time since shutdown, reaching over 1000 percent for some detectors at times greater than 1 year. Also, at a fixed time, the error became larger as the amount of attenuating material between source and detector increased. Finally, the error changed at the same detector point and at the same time for different response units; for example, rads (tissue) versus rads (silicon) versus energy flux. Examples of each of these three results are given below.

For the detector located 170.7 centimeters above the center of the SNAP reactor, the tissue dose rate error between D_1 and D_2 is shown in Table 1. The percent error did not change significantly after 4×10^8 seconds.

TABLE 1. TISSUE DOSE RATE

Time After Shutdown (sec)	Percent Error
1×10^2	0
1×10^3	26
1×10^4	66
1×10^5	283
1×10^6	155
1×10^7	590
1×10^8	509
1×10^9	771
1×10^{10}	770

For 1×10^5 seconds after shutdown, typical detectors showed the discrepancy between D_1 and D_2 for dose rates in rads (tissue) per second (table 2). These detector positions are also ordered in increasing amount of attenuating material between source and detector.

For the detector located at 170.7 centimeters above the center of the SNAP reactor at 1×10^5 seconds after shutdown, the energy flux showed an error of 283 percent, while the tissue dose showed an error of 214 percent. Similarly, at 1×10^9 seconds after shutdown, the energy flux showed an error of 771 percent, while the tissue dose showed an error of 567 percent.

The physical phenomena causing the large discrepancies can be understood by examining the gamma power versus shutdown time curves (figures 1 through 8). These curves show that at early times after shutdown most of the gamma energy is coming from the higher energy gamma groups. As the time after shutdown increases, the percentage of gamma energy emitted in the higher energy groups decreases. For example, approximately one day after shutdown (10^5 seconds), the energy emitted in the highest energy group, VII, is only 0.15 percent of the total. At 10^2 seconds after shutdown, energy group VII contributed 30 percent of the total gamma energy release. As the time after shutdown approaches 10^8 seconds (approximately 3 years), only energy group II contributes significantly to the total decay gamma energy release. Group II covers the energy range from 0.4 to 0.9 MeV. In this energy group, the energy absorption coefficients for all materials are greater than those for the higher energy groups. Hence, this softening of the decay gamma spectrum with increasing time, coupled with the greater absorption coefficients for softer gammas, caused an increased attenuation of the total decay gamma energy. For detectors that are shielded from the decay gamma source, e.g., in a shutdown SNAP-8 reactor, the power ratio assumption for calculating the shutdown gamma dose would not be expected to be very accurate. In fact, the accuracy of the doses calculated by this technique should become poorer as time increases, because of the softening of the decay gamma spectra, and, as the shielding increases, because of the selective attenuation of the lower energy gammas. Also, these phenomena would cause the energy-dependent response functions to show variations.

Although the explanation of the cause of the discrepancies between D_1 and D_2 seemed plausible, the complexity of the source term and the shield geometry in the SNAP-8 reactor system required a check of the validity of the above conclusions. This check was made by calculating the dose from a normalized point source (1 MeV/sec) in each of the Perkins and King energy groups in an infinite water medium. Detectors were located at nine different radii from the point source, beginning at 5 centimeters (5 g/cm^2) and ending at 500 centimeters (500 g/cm^2). Five different responses were calculated; however, only the results of two of the response calculations will be given. These responses are the energy flux (MeV/cm^2-sec) and tissue dose rate [rads(T)/sec]. The effect of time after shutdown and shielding on the tissue dose rate is very similar to the effect on the

TABLE 2. DISCREPANCY BETWEEN D_1 AND D_2

Detector Number	Relative Number of Mean Free Paths	Percent Error
1	1.0	214
2	1.47	333
3	7.90	1,413

TABLE 3. TIME DEPENDENT DECAY GAMMA DOSE COMPARISON

Distance from Source (cm)	Response Function*	Percent Error at Time After Shutdown (sec)								
		10^2†	10^3	10^4	10^5	10^6	10^7	10^8	10^9	10^{10}
5	EF	0.0	0.52	1.11	0.91	0.33	1.13	0.82	2.49	2.49
	TDR	0.0	3.57	6.53	7.59	6.91	12.10	11.90	13.90	13.90
10	EF	0.0	0.74	1.61	1.62	0.95	2.16	1.84	3.50	3.50
	TDR	0.0	3.76	6.97	8.20	7.44	12.90	12.70	14.70	14.70
25	EF	0.0	0.69	1.59	2.83	2.17	1.25	1.32	0.89	0.89
	TDR	0.0	2.60	4.37	4.60	4.99	10.60	10.50	13.00	13.00
50	EF	0.0	7.46	16.30	23.30	18.90	29.80	29.20	26.40	26.40
	TDR	0.0	3.26	8.04	12.40	8.93	11.40	10.90	7.80	7.79
100	EF	0.0	29.90	70.90	105.00	87.20	253.40	248.80	268.10	268.10
	TDR	0.0	24.20	56.60	83.90	69.30	186.10	182.70	192.00	191.90
200	EF	0.0	78.00	242.20	379.70	297.80	3426.40	3210.50	$>10^4$	$>10^4$
	TDR	0.0	72.60	217.80	343.10	270.10	2904.20	2727.60	7885.10	7883.30
300	EF	0.0	111.10	446.70	652.50	495.90	9127.90	8589.90	$>10^4$	$>10^4$
	TDR	0.0	107.80	420.80	624.10	475.60	8396.00	7840.80	$>10^4$	$>10^4$
400	EF	0.0	134.00	673.80	819.10	608.00	$>10^4$	$>10^4$	$>10^4$	$>10^4$
	TDR	0.0	128.80	614.20	806.10	604.30	$>10^4$	$>10^4$	$>10^4$	$>10^4$
500	EF	0.0	143.00	794.70	900.80	670.00	$>10^4$	$>10^4$	$>10^4$	$>10^4$
	TDF	0.0	142.10	781.70	895.30	666.10	$>10^4$	$>10^4$	$>10^4$	$>10^4$

*Detector response are energy flux (EF) in (Mev)/(cm^2·sec) and tissue dose rate (TDR) in [rads (T)/sec].

†Results normalized to 10^2 seconds shutdown time.

other three responses. Table 3 shows that, in general, the results of the decay gamma point source support the conclusions reached above. The percent error increases with increasing time, but not monotonically. The error at 10^6 seconds after shutdown decreases because gamma group IV dominates gamma group II at this time. Thus, this higher percent of high energy gammas emitted at 10^6 seconds more closely approximates the original spectrum (at 10^2 seconds), hence the decrease in percent error between D_1 and D_2. Also, the percent error increases for more shielding, i.e., distance from the source, except at 25 centimeters. The reason for this apparent anomaly is that the build-up of dose is greater than the material attenuation until some point between 10 and 25 centimeters, causing D_2 to be greater than D_1 in this range. From 25 centimeters on, the original conclusion is valid, as expected.

Considering the original results for the SNAP-8 system and the infinite water-point source calculations, the following conclusions were reached:

- The discrepancies between D_1 and D_2 were caused by a decrease in the proportion of high-energy gammas released at longer shutdown times.

- The softening of the decay gamma spectrum with time causes an increased attenuation of decay gamma energy, invalidating the power ratio assumption.

- Energy-dependent calculations need to be made to determine the decay gamma dose rate at various times after shutdown.

Obviously, the energy-dependent calculations of the dose rate are more time-consuming than using the power ratio assumption. However, by using detector positions for which a normalized source-point kernel calculation has been made, and by using figures 2 through 8, the dose rates can be calculated as described below.

Suppose the reactor has operated at a power level of P watts for τ seconds. The conversion factor, C, for data taken from figures 2 through 8 is computed by

$$C = 6.25 \times 10^{12}\ [(\text{MeV/sec})/\text{W}] \cdot P\ (\text{W}) \cdot \tau\ (\text{sec})$$
$$= 6.25 \times 10^{12} \cdot P \cdot \tau\ \text{MeV}.$$

For time of shutdown, t, and for each energy group, determine the corresponding ordinate values from figures 4 through 8. If τ, the operating time, does not equal the operating times on the figures, then use logarithmic interpolation between the given values of τ. The ordinate values are the normalized shutdown gamma power, GP_i, for each of the seven energy groups. Then, for the selected detector position, r, and response, the dose rate at shutdown time, t, operating time, τ, and power level, P, is computed by

$$D\ (r,t) = C \cdot \sum_{i=1}^{7} GP_i(t) \cdot D_i(r),$$

where $D_i(r)$ is the energy-dependent detector response from the normalized source-point kernel calculations. It should be noted that the above process is valid for any shutdown reactor as long as the dose rates are determined for a normalized source (1 MeV/sec) in each of the Perkins and King energy groups.

REFERENCES

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3. Perkins, J. F., "Decay of U-235 Fission Products", U.S. Army Missile Command, Redstone Arsenal, Alabama, Report No. RR-TR-63-11, July 1963

4. Private Communication from M. Burrell and J. Watts, NASA-MSFC, September 1970

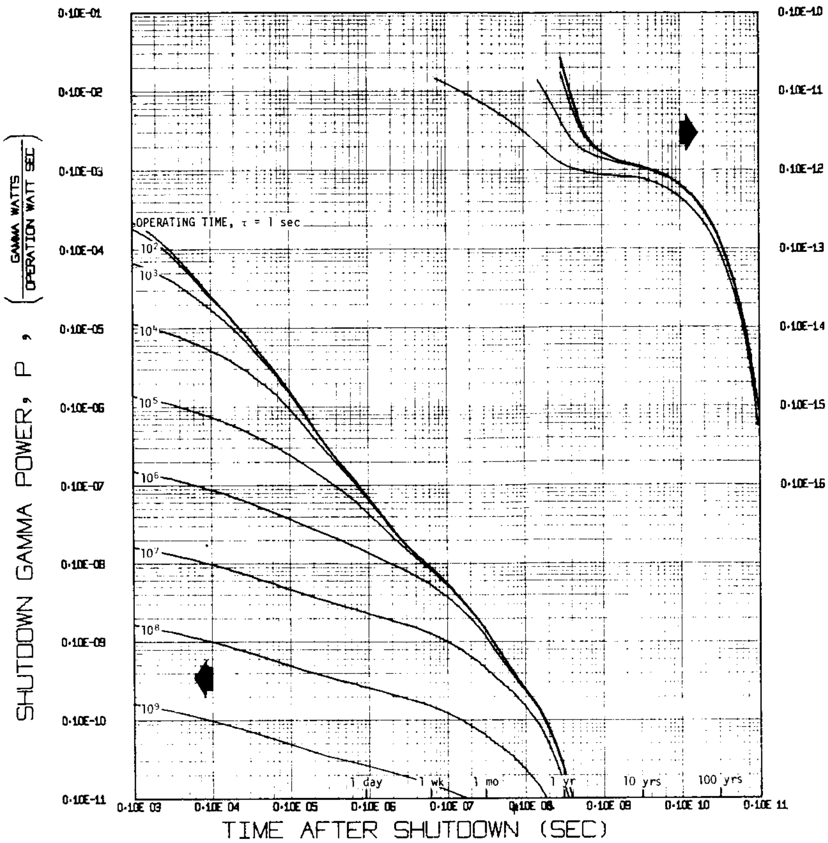

FIGURE 1. - Total shutdown gamma power level.

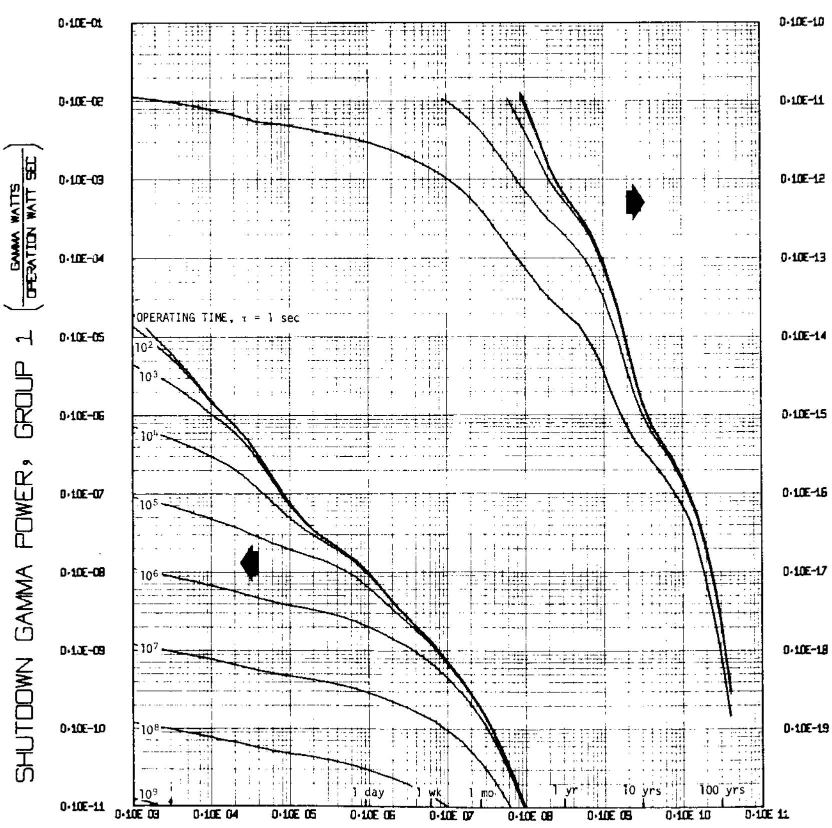

FIGURE 2. - Post shutdown gamma power level energy group (0.1 to 0.4 MeV).

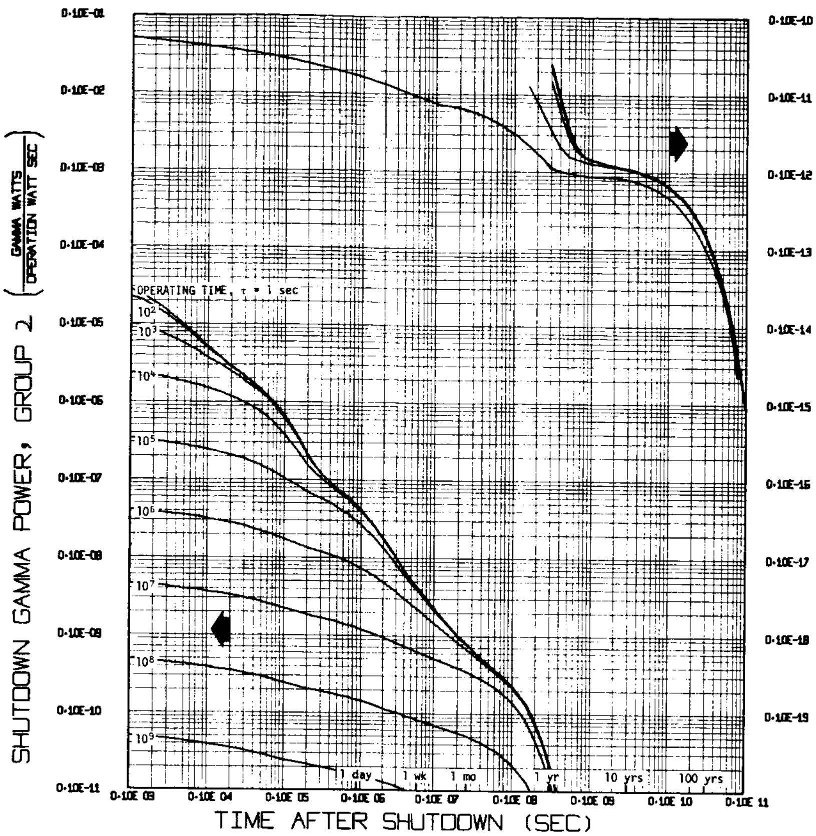

FIGURE 3. - Post shutdown gamma power level energy group (0.4 to 0.9 MeV).

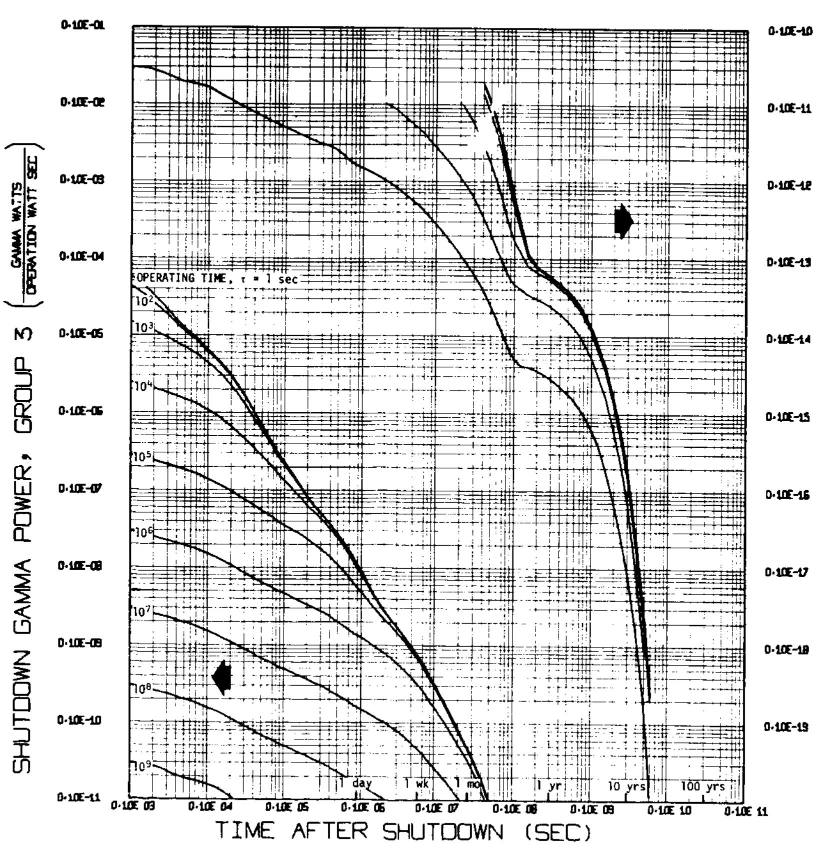

FIGURE 4. - Post shutdown gamma power level energy group (0.9 to 1.35 MeV).

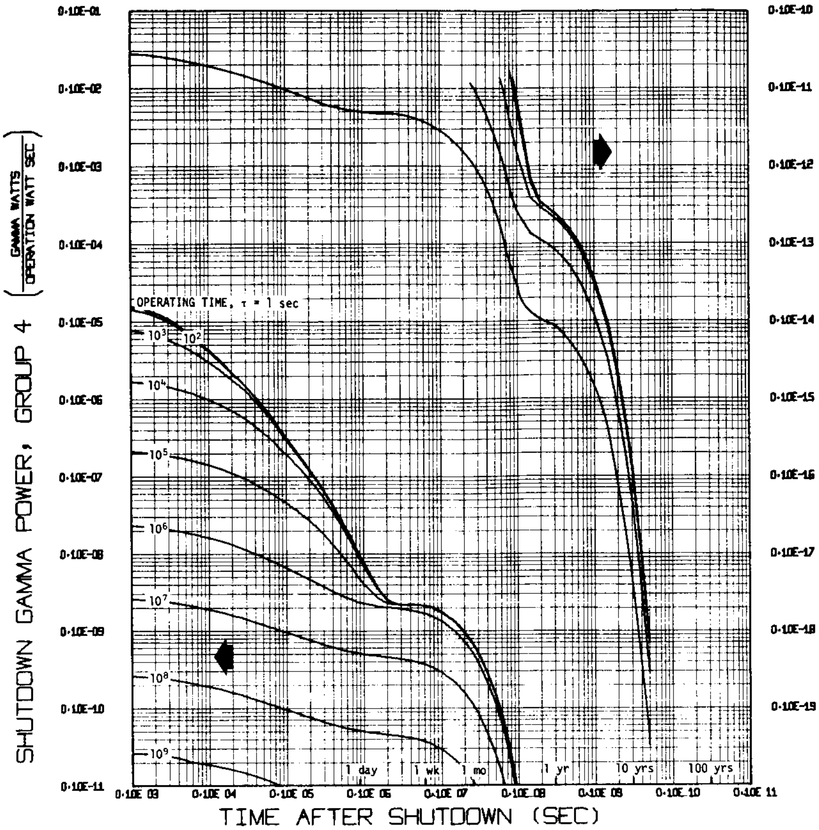

FIGURE 5. - Post shutdown gamma power level energy group (1.35 to 1.8 MeV).

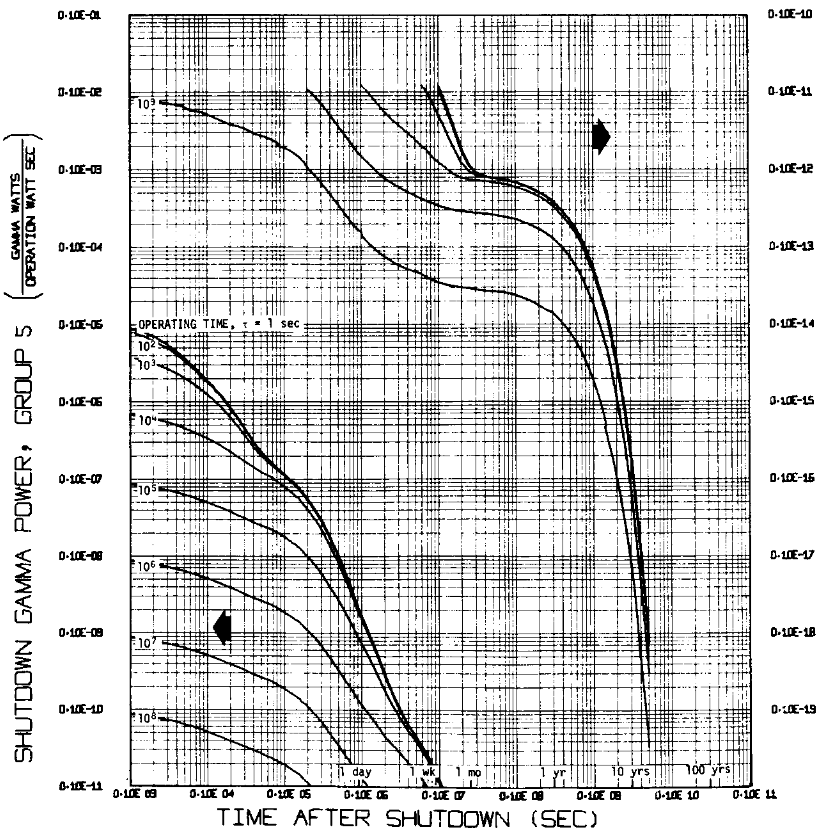

FIGURE 6. - Post shutdown gamma power level energy group (1.8 to 2.2 MeV).

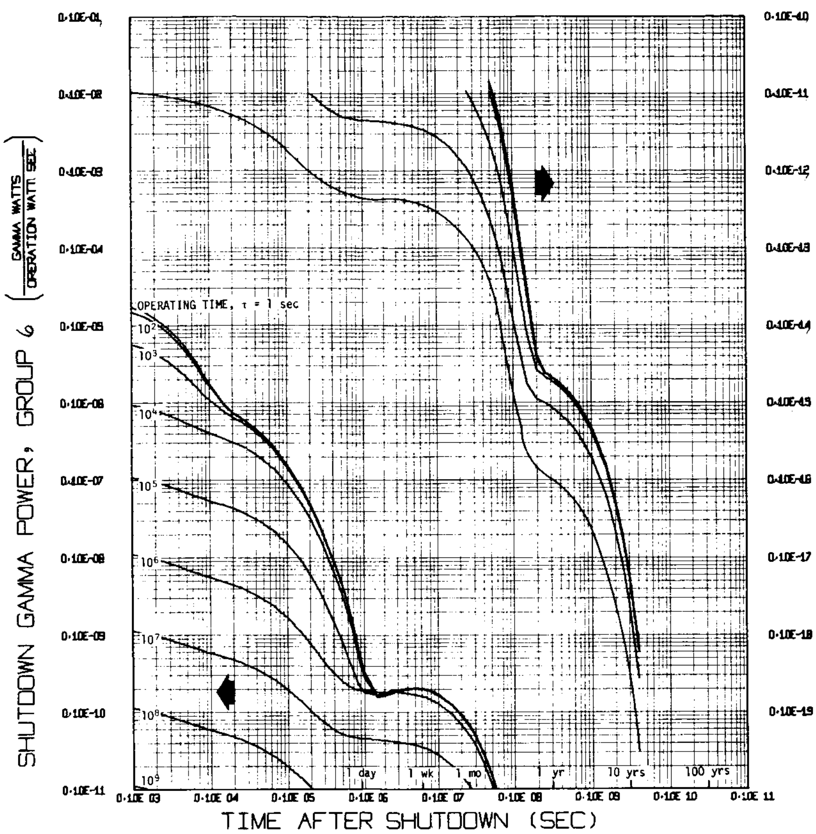

FIGURE 7. - Post shutdown gamma power level energy group (2.2 to 2.6 MeV).

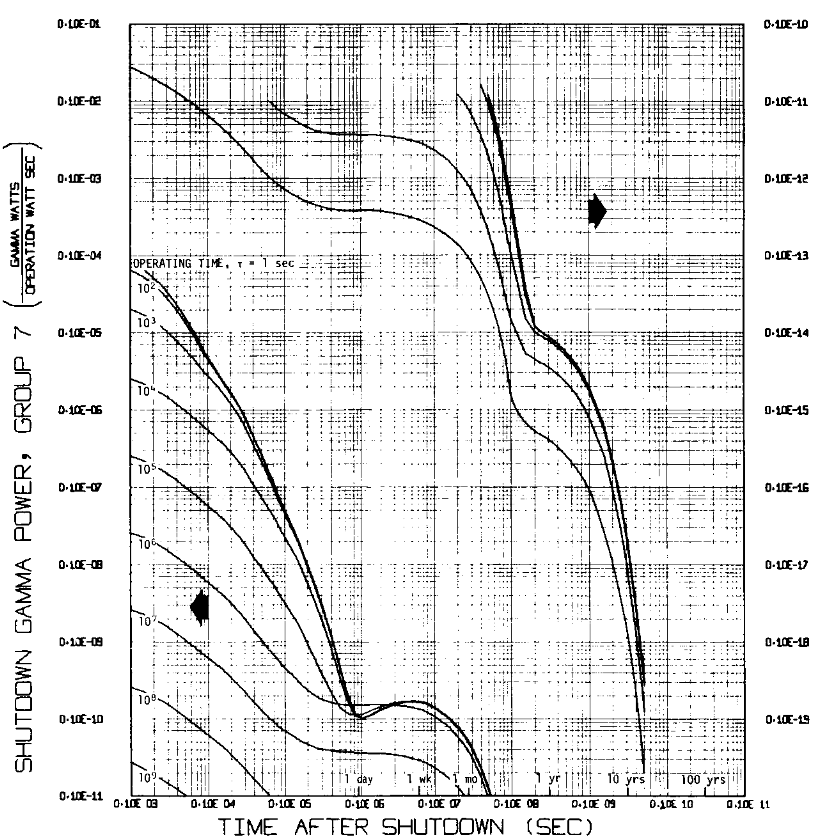

FIGURE 8. - Post shutdown gamma power level energy group (2.6 MeV to ∞).