

tent materials are described in the following subsection, along with the determinants and numerical values of the assimilation half-life used in World3.

The assimilation half-life AHL was defined as the time period, measured in years, over which half of the initial amount of persistent material will disappear from the environment. The assumption and definition may be stated mathematically:

Assumption: $\frac{dPPOL(t)}{dt} = -\frac{PPOL(t)}{C}$

Definition: $PPOL(t = AHL) = \frac{PPOL(t = 0)}{2}$

From equation (6.1): $\frac{dPPOL(t)}{PPOL(t)} = -\frac{dt}{C}$

$$\ln[PPOL(t)] = C' - \frac{t}{C}$$

$$PPOL(t) = [PPOL(t=0)]e^{-\frac{t}{C}}$$

From equations (6.2) and (6.3):

$$PPOL(t=AHL) = PPOL(t=0)e^{-\frac{AHL}{C}} = \frac{PPOL(t=0)}{2}$$

Thus: $e^{\frac{AHL}{C}} = 2$ or $AHL/C = \ln(2)$

and: $AHL/C = 0.7$
 $c = 1.4 AHL$

Therefore: $\frac{dPPOL}{dt} = -PPOL/(1.4 AHL)$

Expressed in the DYNAMO format, equation (6.4) becomes:

$$\begin{aligned} PPAPR, KL &= PPOL, K / (AHL, Y * 1.4) && 144, R \\ PPASR &= PERSISTENT POLLUTION ASSIMILATION RATE \\ &\quad (POLLUTION UNITS/YEARS) \\ PPOL &= PERSISTENT POLLUTION (POLLUTION UNITS) \\ AHL &= ASSIMILATION HALF-LIFE (YEARS) \end{aligned}$$

When the pollution appearance rate PPAPR is zero, one-half of the initial amount of persistent material will leave the environment over a time period equal to one assimilation half-life AHL; after an additional interval equal to AHL, one-fourth of the initial material will still remain, and so forth. The quantity remaining after the passage of a time interval equal to 7 half-lives will be less than 1 percent of the initial amount. Figure 6-17 illustrates the disappearance over time of 100 units of a persistent material with an assumed assimilation half-life of 1.5, 3, 5, and 90 years. Until the level of pollution has risen sufficiently to decrease the assimilative capacity of the environment, the numerical value for AHL employed in World3 is 1.5 years. As a consequence, when the pollution appearance rate is zero, half of the persistent materials will have disappeared from the World3 pollution level within 1.5 years of their appearance. So long as AHL equals 1.5 years, essentially all of the persistent pollutants will have been assimilated in World3 within 10 years after their appearance.

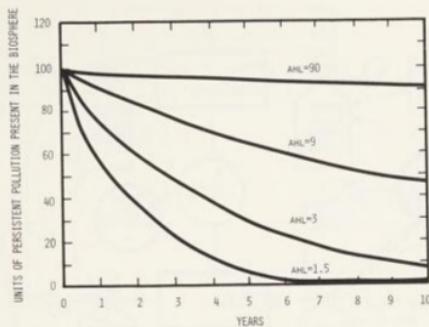


Figure 6-17 The assimilation of 100 units of persistent pollution with various values assumed for the assimilation half-life

Assimilation Half-Life AHL A basic postulate of the persistent pollution sector is that the rate of pollution assimilation at any point in time is directly proportional to the amount of pollution present in the global environment at that time. This assumption was used to derive the preceding expression for the persistent pollution assimilation rate PPASR. The half-life of the assimilation process need not be constant. In fact, the global average pollution assimilation half-life is affected by the composition of the existing pollution load, the geographical distribution of pollution, and the total amount of persistent pollution present in the environment. These three possible influences are discussed in this section to indicate the implications and the basis of our assumption in World3 that the assimilation half-life AHL is a variable that depends only on the level of the pollution present in the biosphere PPOL.

Because the global persistent pollution level will always be composed of materials with different half-lives, the real assimilation half-life will not be constant over time. Materials with very short half-lives disappear quickly. Thus the persistent pollution level PPOL will tend to become composed of materials with longer and longer assimilation half-lives.

This tendency may be illustrated by two simulation analyses of a very simple model of pollution accumulation and assimilation. The flow diagram of a model that simulates the decay of strontium-90 (Sr-90, half-life = 25 years) and molybdenum-93 (Mo-93, half-life = 2 years) is given in Figure 6-18. The program for the model is listed in the Appendix C to this chapter. Figure 6-19A presents a simulation of the model with no inputs of pollution and with initial values of 25 units of Sr-90 and 75 units of Mo-93. At first, the effective half-life of the total pollution level (Mo-93+Sr-90) is about 6 years. After 10 years, however, most of the persis-

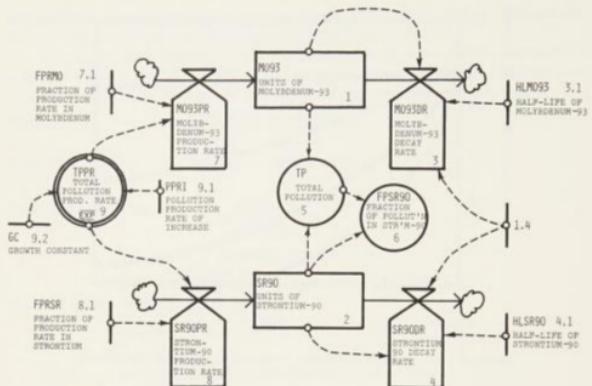
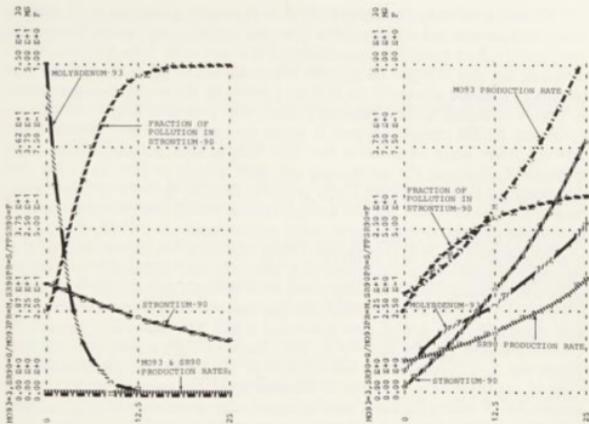


Figure 6-18 DYNAMO flow diagram of a simple model of pollution accumulation and assimilation

Note: Appendix C to this chapter lists the DYNAMO equations of this model.

tent pollution remaining in the system consists of Sr-90, and the effective half-life of the material is 25 years, the half-life of Sr-90. Figure 6-19B, the second simulation of this simple model, illustrates the shift in the composition of persistent pollution that takes place over time when pollution generation is increasing. We start with essentially no pollution in the system and with pollution increasing exponentially at 5 percent per year. Of this newly generated pollution, 75 percent is the short-lived Mo-93 and 25 percent is Sr-90. It can be seen that the composition of the total persistent pollution level gradually shifts from 25 percent Sr-90 to 65 percent Sr-90 at time = 25 years. Initially, the effective half-life of the total pollution is about 6 years; at year 25 it is nearly 20 years.

Although the tendency of effective half-lives to increase with composition changes is potentially important, we concluded that our current knowledge of the future composition of persistent pollution and of the assimilation half-lives that actually characterize persistent materials is too incomplete to warrant incorporating a time-dependent influence on the assimilation half-life in World3. Given the lack of data, incorporating in World3 a tendency for AHL to increase as a function of time due to shifts in the composition of pollutants would not improve the overall projective utility of the model. Although AHL does tend to increase during each simulation of World3, that increase is the consequence of continued growth in the generation and



A. the shift in the composition of total pollution over time with no inputs and initial ratio of 75 percent Mo-93 (half-life = 2 years) and 25 percent Sr-90 (half-life = 25 years)

Figure 6-19 Secular shifts in the composition of total pollution in a simple two-pollution model when the half-lives of the two pollutants are unequal

appearance of persistent pollutants; it is unrelated to a shift in the global composition of persistent materials.

The second influence on the assimilation half-life in the real world is the geographical distribution of the pollutants. The rate of radioactive decay does not depend upon an isotope's concentration. However, where physical sedimentation, biological degradation, or chemical reaction is involved in the assimilation of persistent materials, the physical distribution of the pollutants may have a marked influence on the rate at which they can be assimilated. We chose to ignore this influence in formulating the equation for AHL in World3. By omitting any distributional parameter in the equation that defines AHL, we implicitly assumed that the future distribution of persistent materials around the globe will remain approximately as it was in 1970. While one can argue that the distribution of pollution sources will change in the future, the World3 pollution sector represents the effects of materials that persist long enough to be transported great distances by the globe's air and water streams. Thus the assumption of a constant distribution is not sufficiently in error to alter the utility of the pollution sector.

Assuming that the assimilation half-life AHL is only a function of the quantity of pollutant present, one could conceive of several different relationships between the two variables. Four possibilities are illustrated in Figure 6-20. Line A in each figure represents the case in which the half-life is constant and is independent of the total quantity of pollutant present. If the half-life is constant, the assimilation rate (shown by line A of Figure 6-20B) increases linearly with pollution. Line C (in Figures 6-20A and 6-20B) represents a case in which the assimilation half-life is constant over the lower range of pollution but rises quickly after pollution passes some threshold. In this case the assimilation rate rises linearly at first, as in the case represented by line A, but it ultimately begins to decrease as rising pollution forces the half-life toward infinity and the assimilation rate toward zero. Lines B and D in both figures correspond to other conceivable relationships.

We designed the World3 equations relating AHL to PPOL so that other analysts can easily incorporate the relationship they believe is most reasonable. Because the half-life of each radioisotope is independent of the isotope's quantity, the line relating half-life to the level of a radioactive pollutant is linear with slope zero and thus of the form specified by line A of Figures 6-20A and 6-20B. The relationship between the level of pollutant and the half-life of assimilation through deposition is unclear, though line A of Figures 6-20A and 6-20B may be a useful approximation for that mode of assimilation as well. For information about the form of the relationship between PPOL and AHL that is most appropriate for assimilation through chemical or biological degradation, we employed a simple model of the kinetics of degradation of a single pollutant. The casual reader may omit the mathematical derivation and proceed directly to equation (6.8) of this section.

Some forms of pollution degradation may be carried out by "degraders," which may be small molecules such as oxygen or water, large molecules such as enzymes,

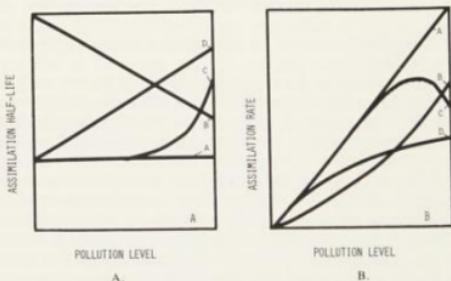


Figure 6-20 Alternative possible relationships between pollution level and assimilation half-life, together with the corresponding rate of pollution assimilation
Note: PPASR = PPOL/(AHL × 1.4).

or entire organisms such as bacteria. For all these the process of pollution degradation could proceed in two steps as follows:



This is a reversible step in which a pollutant P and a degrader D form some kind of intermediate complex.



This is a step in which the complex PD decomposes irreversibly to yield a harmless species H and the degrader D. The degrader is then free for another catalytic cycle.

This formulation is identical to that proposed by Michaelis-Menten to represent enzyme-catalyzed kinetics (Fruton and Simmonds 1958). Following the usual pattern of chemical-kinetic analysis, one presumes a steady-state concentration of the complex PD:

$$\frac{d[PD]}{dt} = 0 = k_1[P][D] - k_1'[PD] - k_2[PD], \quad 6.5$$

where k_1 , k_1' , and k_2 are the rate constants for the indicated reactions. The total degrader concentration, uncomplexed and complex, $[D^*]$ is defined by:

$$[D^*] = [D] + [PD]. \quad 6.6$$

From equation (6.5) at steady state the concentration of the complex PD is

$$[PD] = \frac{k_1[P][D^*]}{k_1' + k_2 + k_1(P)}. \quad 6.7$$

The rate at which the pollutant is assimilated PPASR is the rate of the second step in the reaction mechanism. Thus PPASR = $k_2[PD]$ or

$$PPASR = \frac{k_1 k_2 [P][D^*]}{k_1' + k_2 + k_1(P)}. \quad 6.8$$

From equation (6.8) it is possible to calculate the pollutant's degradation or assimilation half-life AHL:

$$AHL = \frac{[P]}{PPASR(1.4)} = \frac{k_1 + k_2 + k_1(P)}{k_1 k_2 [D^*](1.4)}. \quad 6.9$$

This theoretical model yields AHL as a linear function of $[P]$, the concentration of the persistent pollutant, as shown by Figure 6-21, where $\alpha = (k_1' + k_2)/k_1 k_2 [D^*](1.4)$ and $\beta = 1/k_2[D^*](1.4)$.

Equation (6.8) is a general expression for pollution degradation for which there are two limiting cases. First, if pollution is small relative to the number of degraders, so that $(k_1' + k_2) \gg k_1(P)$, then:

$$PPASR = \frac{k_1 k_2 [P][D^*]}{k_1' + k_2} \quad 6.10$$

and

$$AHL = \frac{k_1' + k_2}{k_1 k_2 [D^*](1.4)}, \quad 6.11$$

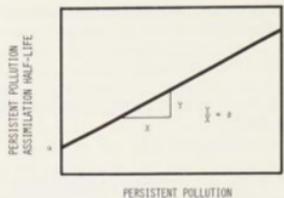


Figure 6-21 The theoretical linear relationship between the persistent pollution assimilation half-life and the level of pollution

indicating that pollution assimilation is proportional to the concentration of pollutants [P] and that the assimilation half-life AHL is constant (line A of Figure 6-20A). If, however, pollution is large relative to the number of degraders, so that $(k_1' + k_2) < < k_1[P]$, then:

$$\text{PPASR} = \frac{k_1 k_2 [P][D^*]}{k_1 [P]} = k_2 [D^*]$$

and

$$\text{AHL} = \frac{[P]}{(1.4)(k_2)[D^*]},$$

which indicates that the degradation rate is no longer determined by the concentration of pollutants but only by the limited concentration of available degraders. In this case the assimilation half-life AHL is directly proportional to the pollutant level (line D of Figure 6-20A).

The foregoing arguments are based on the assumption of a constant total concentration of degraders [D*]. If this concentration changes, then the pollution assimilation rate will have a still more complex behavior. For example, biotic degraders, such as bacteria, may be poisoned by high levels of the pollutant. In this event, [D*] declines as [P] increases, and, from equation (6.9), the pollution assimilation half-life increases with increasing pollution [P] at a greater than linear rate (line C of Figure 6-20A).

An example of a case where the degrader concentration is apparently a function of pollutant levels is provided by the relation of mercury levels to the activity of methylating bacteria. Figure 6-22 presents empirical data suggesting that levels of mercury beyond a certain threshold actually decrease the activity of the bacteria that convert metallic mercury to its organic form. In this case the relationship between AHL and PPOL is indicated by line C of Figure 6-20A.

Even when the distribution and composition of pollution are assumed to be constant, the precise real-world relationship between the level of pollution and the assimilation half-life depends upon the relative importance of the three modes of assimilation—disintegration, deposition, and degradation—and on the magnitude of the half-lives of the individual persistent materials. There is little empirical basis for

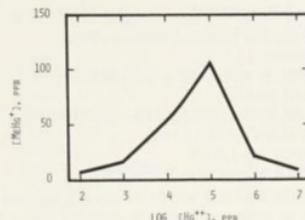


Figure 6-22 Maximum concentration of methylmercury [MeHg+] produced from a given concentration of mercuric ion [Hg⁺⁺]

Source: Anderson et al. 1973.

projecting the future values of either factor over the next several decades. However, we could find no suggestion that persistent materials might be assimilated more quickly as their level in the global environment increases. Thus curve B of Figure 6-20A was not chosen to express the relation between AHL and PPOL. Instead we incorporated in World3 a linear relationship belonging to the same class as curve D of Figure 6-20A. However, because the relationship is highly uncertain, we made AHL a function of the pollution index PPOLX rather than of pollution PPOL itself.

While some set of precise equations must be developed to express the influence of the pollution level on AHL, it is important to develop the equations in a form suited to the low level of information actually available. To illustrate this important point we give two different statements expressing the same relationship between the level and the assimilation half-life of persistent pollution. The first suggests a rather comprehensive knowledge about the nature and the precise magnitude of all influences on the assimilation half-life. The second conveys a lower level of knowledge. We would say that the first statement implies a ratio scale for pollution and assimilation half-life. The second statement implies only an interval scale.* The DYNAMO equations appropriate for each scale are given below the corresponding statement.

1. Statement implying a ratio scale:

The assimilative half-life of the biosphere is a linearly increasing function of the level of pollution present. When pollution is less than 10^0 units, the assimilation half-life will be 1.5 years. For each additional 25×10^0 units of persistent pollution beyond 10^0 units, assimilation half-life AHL will increase by 1.5 years.

DYNAMO Equations:

$$A \text{ AHL.K} = TABHL (\text{AHLT}, \text{PPOL.K}, 1E8, 1001E8, 250E8)$$

$$T \text{ AHLT} = 1.5 / 16.5 / 31.5 / 46.5 / 61.5$$

2. Statement implying an interval scale for pollution and assimilation half-life:

If persistent pollution rises to 1,000 times its level in 1970, the assimilation

*For a useful discussion of the difference between ratio and interval scales see Blalock 1960.

half-life would be about 40 times as great as it was in 1970.* The global assimilation half-life was about 1.5 years in 1970.

DYNAMO equations:

$$\begin{aligned} A \text{ AHL.K} &= \text{AHL70} \times \text{AHL.M.K} \\ C \text{ AHL70} &= 1.5 \\ A \text{ AHL.M.K} &= \text{TABHL}(\text{AHLMT}, \text{PPOLX.K}, 1, 1001, 250) \\ T \text{ AHLMT} &= 1/11/21/31/41 \\ C \text{ PPOL70} &= 1.36E8 \\ A \text{ PPOLX.K} &= \text{PPOL.K}/\text{PPOL70} \end{aligned}$$

Our information about the real world's current and potential assimilation capacity is based primarily on intuitive impressions, scattered data, and case studies. The interval-scale statement is closer to our current level of understanding than the ratio-scale statement. Existing information is not precise enough to connect absolute pollution levels directly with absolute values for the assimilation half-life AHL. However, there is some basis for guessing the percentage increase in the assimilation half-life that would be produced by different increases in PPOL. In the interval formulation one may easily change the value of the assimilation half-life in 1970, the value of persistent pollution in 1970, or the rate at which the assimilation half-life would increase with increases in the persistent pollution levels. Both DYNAMO expressions are numerically identical and would lead to the same model behavior, but the first equation does not clearly exhibit the components of the judgment that lead to the assessment of pollution's influence on AHL. We therefore chose the interval formulation. If more comprehensive and accurate information were available, the ratio expression would be preferred.

Since the assumptions underlying our formulation of AHL refer to the situation in 1970, the normalizing constant PPOL70 must always be equal to the value computed in World3 for persistent pollution PPOL in 1970. If any change is introduced in World3 that directly or indirectly influences the persistent pollution generation rate PPGR, transmission delay PPTD, or assimilation rate PPASR, and thereby the value of persistent pollution PPOL in 1970, the constant PPOL70 will have to be changed so that PPOLX will still retain the value of 1.0 in 1970. The standard value for PPOL70 was determined by simply simulating the standard version of World3 and setting PPOL70 to the value of PPOL observed in 1970. Since PPOL70 has a slight and indirect influence on the level of persistent pollution through AHL, several iterations were required to find the precise value of PPOL70 that caused PPOLX to be 1.0 in 1970.

Although current information is insufficient to make any accurate estimates of the effective assimilation half-life of global persistent pollution in 1970 AHL70, there are data that indicate the half-lives of individual persistent materials present in the environment in 1970. Figure 6-23 summarizes the estimates of the half-lives in soil of ten insecticides made by Nash and Woolson (1967). The estimated half-lives range from 4 to 13 years. It should be noted that these figures are not accurate estimates of the half-lives of these materials in the global environment, for disappear-

| Insecticide | Half-life in Soil (years) |
|----------------------|------------------------------|
| Aldrin | 11 |
| Chlordane | 11 |
| Endrin | 11 |
| Heptachlor | 5 |
| Dilan | 6 |
| Isodrin | 5 |
| Benzene hexachloride | 4 |
| Toxaphene | 12 |
| Dieldrin | 9 |
| DDT | 13 |

Figure 6-23 Disappearance half-lives for ten insecticides in soil

Source: Data from Nash and Woolson 1967.

ance from the soil is a necessary but not a sufficient condition for disappearance from the global environment. Some fraction of the pesticides that vanished from the soil in Nash's tests must have been degraded and thus fully assimilated. The remainder may have simply evaporated and moved to other sectors of the global environment.

The difference between disappearance from only one sector and full assimilation by the global environment is illustrated by the simulation of our DDT model (Randers 1973), in which we followed the disappearance of the insecticide from the various sectors of the global environment after an initial pulse application in year 10 of the simulation (Figure 6-15). The residence half-life of DDT in the soil is seen to be about 2 years.* However, it takes fully 17 years to achieve a 50 percent reduction in the total amount of the chemical present in the environment: the air, soil, stream, ocean, and fish sectors of the model.

Figure 6-24 provides data on the half-lives of radioisotopes released in the liquid wastes of conventional pressurized water reactor nuclear power stations. The half-lives range from 20 hours to about 28 years. The concentration of these materials in the liquid effluents of reactors was extremely small in 1970, so they did not play a significant role in determining the effective assimilation half-life of the total global persistent material burden. However, both the growth in reactor usage and the tendency of longer-lived materials to increase in importance because of changes in the composition of persistent materials will increase the contribution of many elements listed in Figure 6-24 to the global pollution burden.

As a final illustration of the half-lives that characterize current components of the global persistent material burden, we refer again to our simulation of the mercury model (Figure 6-16). In the model's projection, only a small fraction of the total metal initially added to the environment disappears from the air, soil, mud, ocean, and fish sectors of the model after 140 years have elapsed. This long delay is likely to

*To obtain equally spaced table intervals, DYNAMO programming conventions force the use of 1,001 instead of 1,000 as the upper bound of the AHLMT table. Obviously, this difference has no effect on the model's behavior.

*The discrepancy between our simulated estimate of half-life in soil and the larger figure obtained by Nash and Woolson (1967) is due to the higher rate of evaporation in the simulated system. Nash placed his DDT evenly throughout several inches of soil. Thus evaporation was less important in his test than in the real world.

| Isotope | Half-life |
|---------|------------|
| H-3 | 12.3 years |
| Mn-54 | 300 days |
| Co-58 | 71 days |
| Co-60 | 5.2 years |
| Sr-89 | 50.5 days |
| Y-90 | 64.8 hours |
| Y-91 | 57.5 days |
| Mo-99 | 67 hours |
| I-131 | 81 days |
| Cs-134 | 2.3 years |
| Te-132 | 78 hours |
| I-133 | 20.5 hours |
| Cs-136 | 13 days |
| Cs-137 | 27 years |
| Ba-140 | 12.8 days |
| La-140 | 40.5 hours |
| Ce-144 | 290 days |

Figure 6-24 Half-lives of radioisotopes present in the liquid releases from a 1,000-megawatt pressurized water nuclear reactor.

Source: Data from Wright 1970.

be characteristic of most heavy metals, which currently constitute an important portion of the globe's persistent pollution level. We could find no accurate means of weighing even the current components of pollution in an assessment of the effective half-life. We therefore chose a conservative figure of 1.5 years for the assimilation half-life of persistent pollution AHL in World3 in 1970.

Having assumed a linear relationship between the assimilation half-life AHL and the index of pollution^{*} PPOLX and having specified the magnitude of AHL in World3 in 1970, we needed only to estimate the slope β of the line relating the two. For a specific pollutant the slope could in theory be calculated from the kinetic rate constants as indicated earlier. Where a wide variety of pollutants is involved, some other basis for an estimate had to be found. Our approach was to determine the dynamic significance of β , the slope of the line relating AHL and PPOLX.

Given our assumption that AHL is a linear function of PPOLX,

$$\begin{aligned} \text{AHL} &= \text{AHL70} (1 + \beta \times \text{PPOLX}) \\ &= \text{AHL70} (1 + \beta \times \text{PPOL/PPOL70}). \end{aligned}$$

Thus:

$$\text{PPASR} = \frac{\text{PPOL}}{\text{AHL70}(1 + \beta \times \text{PPOL/PPOL70})} \quad (1.4)$$

In 1970 the assimilation rate is:

$$\text{PPASR}(1970) = \frac{\text{PPOL70}}{\text{AHL70}(1 + \beta)} \approx \frac{\text{PPOL70}}{\text{AHL70} \times 1.4}$$

*It should be noted that the AHL relationship assumed for the model runs is slightly nonlinear, for AHL is assumed to be constant at 1.5 years when PPOLX is less than 1.0. The resulting behavior is indistinguishable from an assumed linear AHL relationship.

The approximation is valid since we assume that β is substantially less than 1.0.

To estimate the approximate value of β , we may compute the maximum value for the assimilation rate PPASR, which occurs when the pollution level approaches infinity. If we allow pollution to grow toward infinity ($\text{PPOL} \gg 1$), then:

$$\begin{aligned} \text{LIM}_{\text{PPOL} \rightarrow \infty} \text{PPASR} &= \text{LIM}_{\text{PPOL} \rightarrow \infty} \frac{\text{PPOL}}{\text{AHL70}(1 + \beta \times \text{PPOL/PPOL70})} \quad (1.4) \\ &= \frac{\text{PPOL70}}{\text{AHL70}(\beta)} = 1/\beta \times \text{PPASR}(1970). \end{aligned}$$

Thus, given a linear relationship between AHL and PPOL, at very high levels of persistent pollution PPOL, pollution assimilation PPASR becomes a constant independent of PPOL and equal to the reciprocal of β times the assimilation rate observed in 1970. This is just a restatement of the limiting case for assimilation found in the simple kinetic model derived earlier in this chapter. It is thus clear that β can be evaluated by intuitively estimating the relationship between the assimilation rate in 1970 and the maximum assimilation rate that could be sustained by the global environment. We assumed that the environment could assimilate up to 25 times the amount of pollutants it rendered harmless in 1970. Thus β was set equal to 0.04 in the standard version of the World3 program. However, we tested the sensitivity of the pollution sector's behavior mode to a variety of other assumptions about the maximum possible assimilation rate. It should be noted that so long as AHL is not zero, growth in the level of persistent pollution PPOL will accompany an increasing generation rate PPGR even if the assimilation capacity of the environment is assumed to be infinite. The form of the standard relationship between PPOLX and the multiplier on the assimilation half-life in 1970 AHL70 is shown in Figure 6-25.

AHLM, K=TAHMLT(AHLM,PPOLX,K,1,1001,250)
AHLM70=1/11/21/31/41
AHLM = ASSIMILATION HALF-LIFE MULTIPLIER
(DIMENSIONLESS)
TAHMLT = A FUNCTION WITH VALUES SPECIFIED BY A TABLE
AHLM = AHL TABLE
PPOLX = INDEX PERSISTENT POLLUTION
(DIMENSIONLESS)

AHLM, K=AHLM70*AHLN, K
AHLM70=1, S
AHL = ASSIMILATION HALF-LIFE (YEARS)
AHL70 = ASSIMILATION HALF-LIFE IN 1970 (YEARS)
AHLN = ASSIMILATION HALF-LIFE MULTIPLIER
(DIMENSIONLESS)

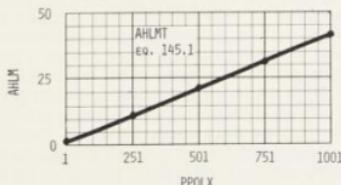


Figure 6-25 Table function of the relationship between PPOLX and the multiplier on the assimilation half-life in 1970 AHL70.