California Institute of Technology

ENVIRONMENTAL QUALITY LABORATORY

TIME FACTORS IN SLOWING DOWN THE RATE OF GROWTH OF DEMAND FOR PRIMARY ENERGY IN THE UNITED STATES

by

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SUMMARY

The purpose of this report is to identify the time scales involved in slowing down the rate of growth of primary energy consumption in the U. S., as one component of an overall energy/environment strategy designed to limit the required volume of energy imports from overseas. Two important energy-consuming sectors of the economy are chosen as illustrative examples: (1) the "automobile" as a total system (25%); (2) space heating, air conditioning and water heating in the residential sector (22%). Efficient, light-weight vehicles are introduced into the automobile population by allocating an increasing percentage of new car production to such vehicles year by year until some fixed percentage is attained. Parametric calculations show that significant reductions in the annual rate of energy consumption by automobiles can be achieved if (a) the fuel consumption of efficient vehicles is 60% or less of "standard" vehicles; (b) the increment in percentage of new car production devoted to efficient vehicles is not less than 8% per year; (c) the efficient vehicles are "frozen" at not less than 80% or more of all new car production at the end of an eight to ten year period. In the residential sector the "turnover" rate is comparatively low, and the calculated reduction in annual energy growth rate produced by energy-conserving measures is modest, as expected, unless a "retrofit" rate of older living units of at least 2% per year can be attained.

These two components of an energy-conserving policy taken together would bring the growth rate in U. S. primary energy demand down from its present rate of 4.2% per year to about 2.8% per year by 1985. Reductions in the annual growth rate of the remaining 50% of U. S. primary energy consumption that seem quite feasible would bring the overall growth rate down to about 2.5% per year by 1985. If reductions in growth rate of this magnitude could in fact be achieved, energy imports would peak in the mid-1980s at a level no higher than about 60% above the present (1973) volume of imports. Incentives and disincentives designed to bring about this slowdown in the rate of U. S. energy consumption are discussed briefly.

1. Introduction

Until quite recently it was generally assumed that the rate of supply of primary energy from domestic sources would always be adequate to meet the steadily rising rate of demand for energy in the U. S. The "energy crunch" of the 1970s shows that this assumption is no longer valid. During the decade from 1960 to 1970 total U. S. primary energy consumption grew at an annual rate of 4.3%,[1]* corresponding to a "doubling time" of about 16 years. In this same period domestic energy production grew at an annual rate of 2.6%, corresponding to a doubling time of about 27 years. The inevitable consequence of these mismatched time scales of domestic energy supply and demand was that the U. S. shifted its position from a net exporter to a net importer of energy in the late 1960s.

Any viable energy strategy for the next 25 years must contain a "mix" of the following sets of measures:

(a) increasing the rate of imports of oil and liquefied natural gas (LNG);

(b) increasing the rates of supply of primary energy from domestic sources, especially uranium and coal (including coal gasification and liquefaction), and, to a lesser extent, oil and natural gas;

(c) developing new sources of energy, such as geothermal and solar energy (esp. solar/thermal conversion);

(d) slowing down the rate of growth of energy consumption by improving efficiency, reducing "wasteful" practices, and shifting to less energy-intensive activities.

Each of these sets of measures has its own characteristic time scale, or doubling time, and these competing time scales will determine the nature of the "mix". These characteristic time scales are governed in turn by a complex set of logistical, technical, economic, environmental, land use, institutional and political-legal constraints. The authoritative study by the National Petroleum Council has already examined in detail the range of possibilities under option (b) above.[1,2] The purpose of the present report is to identify the time scales and magnitudes of option (d) – slowing down the rate of growth of energy consumption – by means of a few highly-simplified but typical illustrative examples. The results obtained are then examined for their impact on the required rate of energy imports and the required rate of domestic energy supply over the next 25 years.

* Superscripts denote references listed at the end of this report.

The question as to whether reductions of significant magnitude in the annual rate of growth in the demand for energy can actually be achieved over the next 10-15 years was addressed in the NPC demand projections[2] for 1985. In these projections the "low" estimate lies about 10% below the "intermediate" estimate. The recent Office of Emergency Preparedness report[3] on energy conservation projects a decrease of about 15% in energy demand by 1985 if all "mid-term" conservation measures are employed, and a decrease of about 22% if all "long-term" measures are utilized (Fig. IX-1, p. 59 of Reference 3). Beyond 1985 the various estimates of energy demand diverge somewhat, as expected, because of the difficulties involved in making such projections. For example, in 1995 the NPC "low" demand estimate is only 13% lower than the intermediate estimate, while the OEP estimated demand (extrapolated) is reduced by about 17% if "mid-term" conservation measures are employed, and by about 27% if all "long-term" measures are used.

In order to examine this question more carefully two important energy-consuming sectors of the economy are chosen in this report for purposes of illustration: (1) transportation (25%); (2) space heating, air conditioning and water heating in the residential sector (22%). The 25% of U. S. primary energy consumed in transportation is fuel alone, of which automobiles consume somewhat more than one-half, or about 14% of U. S. primary enregy. However the "automobile" considered as a total system all the way from raw materials through production, distribution, road-building, servicing and repair consumes 25% of all U. S. primary energy,[4] so the automobile is singled out for special attention in Section 2. "Efficient", light-weight vehicles are introduced into the automobile population by devoting an increasing percentage of new car production to such vehicles year by year until some fixed percentage is attained. The effect of this shift on the rate of growth of energy consumption is calculated over a 20-year period.

In Section 3 a similar study is carried out for the residential sector. Energy-conserving living units are introduced by increasing their percentage of new unit construciton year by year until some fixed percentage is attained.

These two sectors differ in one important respect: the annual "birth" and "death" rates of automobiles are relatively high (11% and 7% of the existing car population, resp.), so the time scale for making changes in the rate of growth of energy-consumption of automobiles is relatively short (of the order of 6-10 years), and the magnitude of the reductions in growth rate is significant. On the other hand the annual "birth" and "death" rates of residential units are relatively low (3% and 1% of the existing living units, resp.), so changes in the annual rate of growth in energy-consumption are correspondingly slower, and of smaller magnitude, unless a significant percentage of older structures can be "retrofitted" to conserve energy. These points are brought out by means of some simple illustrative examples in Section 3.

Finally, Section 4 examines the implications of the results obtained in Section 2 and 3 for energy imports, domestic energy supplies, and U. S. energy policy alternatives.

2. Slowing the Rate of Growth of Energy Consumption by Automobiles

At any given time the automobile population is characterized by a wide "performance" spectrum in terms of miles per gallon, ranging at present from values as low as 7 miles per gallon to a high of around 28 miles per gallon. In order to bring out the importance of time scales in reducing the rate of energy consumption as simply as possible, we will work with a population consisting of only two classes of vehicles: (1) "standard" vehicles, all of which require $g_1(t)$ gallons per mile; (2) "efficient" vehicles, all using $g_2(t)$ gallons per mile, where $g_2 < g_1$. In this case the annual energy consumption rate, E, is given by the following expression:

$$\frac{E}{E_0} = \frac{m}{m_0} \frac{g_1}{(g_1)_0} \left[\frac{n_1}{n_0} + \frac{g_2}{g_1} \frac{n_2}{n_0} \right] \quad (1)$$

Here m is the average annual mileage per vehicle, n_1 and n_2 are the number of standard and efficient vehicles, resp., and $n = n_1 + n_2$ is the total number of automobiles at any given time. The subscript zero refers to the "base" year (say 1973) that is selected as the starting point for calculating the time history of the annual rate of energy consumption.

Suppose that all vehicles are standard vehicles at the beginning of the base year, i.e., $n_1 = n_0$ and $n_2 = 0$. In this simple example the process of introducing efficient vehicles into the automobile population is divided into two stages: In the first stage a steadily increasing percentage of new car production is assigned to such vehicles, e.g., 10% of all new cars during the first year, 20% the second year, etc., until the jth year ($j \leqslant 10$ in this example). After the jth year the percentage of new car production taken up by efficient vehicles is fixed at (10j)%. For simplicity the death rate of efficient vehicles is taken to be zero during the first j years, while the death rate of standard vehicles is some function d(t). Beyond the jth year the death rates of the two classes of vehicles are assumed to be the same.*

* This approach is easily generalized by allowing the percentage of new cars that are efficient vehicles to be equal to p the first year, 2 p the second year, etc., up to the jth year ($jp \leqslant 100$), where $0 \leqslant p \leqslant 100$. Beyond the jth year efficient vehicles are a fixed percentage jp of all new car production (Appendix).

At the present time the birth rate, b, and the death rate, d, of the total automobile population are 11% and 7% per year, respectively, so the total population is growing at an equivalent exponential rate of 4% per year. Taking these rates as fixed for the present, and considering the process as a continuous one, the differential equations describing the time history of the automobile population in this simple illustrative example can be written down and readily integrated to give the time histories of standard $n_1(t)$ and efficient vehicles $n_2(t)$. (See Appendix)

Actually the first and simplest case analyzed turned out to contain most of the "message". In this case the percentage of new car production allocated to efficient automobiles increases by 10% each year up to the tenth year, when these vehicles constitute 100% of new car production (Case 1, j = 10, p = 10%). No new standard automobiles are produced thereafter. The automobile population history for Case 1 is shown in Figure 1. The population of standard vehicles peaks between the third and fourth years, when the birth rate of this class of vehicle is equal to its death rate. Beyond this point the population n_1 declines more and more rapidly, and, in fact, for $t \geqslant 10$, n_1 declines exponentially with time, because no new standard vehicles are being produced. The population of efficient vehicles builds up quite slowly at first (Figure 1), but increases rapidly beyond $t = 4$. By about the tenth year efficient vehicles account for one-half the total car population (Figure 1). If this process were to continue indefinitely with time, the build-up of efficient vehicles would approach the equivalent exponential rate of 4% per year.

At present the average mileage driven per automobile is increasing by 1% per year, i.e., $\frac{m}{m_0} = e^{0.01t}$. By adopting this rate in our calculations, and by utilizing the results for n_1 and n_2 in [Eq. (1)], the time history of the energy-consumption rate is calculated for various values of the fuel economy parameter $\frac{g_2}{g_1}$ between 0.50 and 1.0; the results are illustrated in Figure 2. For comparison the growth in $\frac{E}{E_0}$ is also shown for a car population consisting only of standard vehicles ($n_2 = 0$), i.e., $\frac{E}{E_0} = e^{0.05t}$.* At present the average gasoline consumption for U.S. automobiles is about 15 miles per gallon,[4] so values of g_1 of 0.750, 0.625 and 0.50 correspond to 20, 24 and 30 miles per gallon, respectively.

* According to Eq. (1) for various values of $\frac{g_2}{g_1}$ between 0.50 and 1.0 the value of $\frac{E}{E_0}$ at any given time can be found by means of a linear interpolation.

Values of $\frac{g_2}{g_1}$ in the neighborhood of 0.5 to 0.6 are required for this particular population time history in order to produce a substantial reduction in the annual *rate of growth* of E. During the first three or four years the influence of the efficient vehicles is small (as expected), but by about the sixth year the annual rate of growth would be brought down from 5% per year to about 1% per year if $\frac{g_2}{g_1}$ = 0.625, and to virtually zero if $\frac{g_2}{g_1}$ = 0.50, and it would remain at these low values until about the tenth year. If these results are applied to the automobile as a total system (25% of all U. S. primary energy demand), this reduction amounts to a decrease of about 1% per year in the overall energy growth rate (e.g., from 4.2% to 3.2% per year), if g_1 = 0.625.

Beyond t = 10 the annual rate of energy consumption increases again (Figure 2), and gradually approaches the equivalent exponential rate of 5% per year, although even at t = 20 the *level* of energy consumption rate for $\frac{g_2}{g_1}$ = 0.50 is still only 60% of the projected value for an all-standard vehicle population. This interim period of slow annual growth rates provides a "breathing space", or an equivalent time shift of at least ten years. During this time period new factors and new measures can be introduced to slow the overall rate of growth of the automobile population. (See Section 4)

The question naturally arises as to the sensitivity of the magnitude of the slowdown in the rate of energy–consumption to the introduction of certain exhaust emission controls $\frac{g_1}{(g_1)_0}$, ; to the yearly increment in percentage of new car production allocated to efficient vehicles (p), and to the "frozen" level of new car production for such vehicles [(pj)%]. In order to answer this question three additional illustrative cases were considered.

In Case 2, j = 10 and p = 10% as before, but $\frac{g_1}{(g_1)_0}$ is allowed to increase at a uniform rate from 1.0 to 1.15 during the first three years in order to take into account the effect of certain exhaust emission controls on the performance of present-day engines. Beyond the third year $\frac{g_1}{(g_1)_0}$ = 1.15. The values of $\frac{g_2}{g_1}$ for Cases 2a – 2c are the same as for Cases 1a – 1c. Based on the projected 15% increase in fuel consumption imposed by new exhaust emission controls, the "standard" vehicle would obtain about 12 miles per gallon and values of $\frac{g_2}{g_1}$, of 0.750, 0.625 and 0.50 would correspond to 16, 19 and 24 miles per gallon, resp.

Figure 3 shows the energy-consumption history for Case 2, and Figure 4 compares Cases 1c and 2c in order to illustrate the effects on the rate of energy-consumption of exhaust emission controls installed on both new and old vehicles. Clearly the situation is going to get worse before it gets better. Even with the introduction of the new, efficient vehicles the annual rate of energy consumption is higher up to the seventh year than the level reached by a 5% per year projected increase. However, the *rate of growth* of the annual energy-consumption rate is again reduced to about 1% per year between the sixth and tenth years if $\frac{g_2}{g_1} = 0.625$.

Figures 5 and 6 show the effect of "freezing" the percentage of new car production devoted to efficient vehicles at 50% after the fifth year ($j = 5$), at 60% after the sixth year ($j = 6$), etc., for the particular case $\frac{g_2}{g_1} = 0.50$, $\frac{g_1}{(g_1)_0} = 1.0$, $p = 10\%$ (Case 3). These results show that significant reductions in the annual rate of growth of energy-consumption are achieved only if $j \geqslant 8$, i.e., if the efficient vehicles are "frozen" at not less than 80% of all new car production after the eighth year.

Suppose that the process of introducing these efficient vehicles is slowed down so that some yearly incremental percentage of new car production less than 10% is employed ($p < 10\%$). The effects of this "stretchout" are shown in Figures 7 and 8 (Case 4, $j = 10$, $\frac{g_2}{g_1} = 0.50$, $\frac{g_1}{(g_1)_0} = 1.0$). Evidently significant reductions in the annual rate of growth of energy-consumption are attained only if the incremental percentage of new car production devoted to efficient vehicles is not less than about 8% per year over an eight to ten year period.

3. Slowing the Rate of Growth of Energy Consumption in the Residential Sector

As in the case of automobiles, for simplicity we are going to work with a "bimodal" population of dwellings consisting of only two classes: (1) "standard" dwellings that consume e_1 units of primary energy annually on the average; (2) "energy-conserving" structures that consume e_2 units of primary energy annually on the average. With this simple model the annual rate of energy consumption E is given by the following expression:

$$\frac{E}{E_0} = \frac{e_1}{(e_1)_0}\left[\frac{n_1}{n_0} + \frac{e_2}{e_1}\,\frac{n_2}{n_0}\right] \qquad (2a)$$

or,

$$\frac{E}{E_0} = \frac{e_1}{(e_1)_0}\,\frac{n}{n_0}\left[1 - \left(1 - \frac{e_2}{e_1}\right)\frac{n_2}{n}\right] \qquad (2b)$$

where n_1 and n_2 are the number of standard and energy-conserving dwellings or living units, resp., and $n = n_1 + n_2$. The subscript zero again refers to the "base" year.

Suppose that all structures are standard in the base year, and that 10% of all new living units built in the first year are energy-conserving, 20% the second year, etc., up to the tenth year, after which time all new dwellings are energy-conserving. During the same period suppose that a certain percentage (100 R)% of standard living units are "retrofitted" annually so that they consume only e_2 units of primary energy per year.*

At present the annual rate of construction of new living units is about 3% of the existing population, and the demolition rate is about 1% per year. Considering all these processes as continuous the differential equations describing the time history of the population of living units can be formulated and integrated to obtain the time history of the living unit "population" (Appendix). In this simple example the assumption is made that no energy-conserving structures are demolished during the first ten years, but that after that time the demolition rate for these units is the same as for "standard" units.

* If more detail is warranted in the calculation, one could consider three classes of structures: (1) standard; (2) energy-conserving; (3) standard structures that are retrofitted.

In Figure 9 the population history of standard and energy-conserving living units is shown for retrofit rates of zero, 1%, 2%, and 3% per year, resp. (Also shown is the growth of the total population, $n = n_0 e^{0.02t}$). For $R = 0$ the population of standard dwelling places peaks between the sixth and seventh years, and then decays very slowly with time. The population of energy-conserving dwellings builds up very slowly, and even after 14 years, these units comprise only about 23% of the total population. On the other hand if the retrofit rate is 2% per year the build up of energy-conserving units is much faster, and these dwelling places amount to about 40% of the population after 14 years.

At present the annual consumption of primary energy per residential unit is growing at about 3% per year, or $\frac{e_1}{(e_1)_0} = e^{0.03t}$. Taking this growth rate as fixed for the present, the effects of introducing new energy-conserving structures and retrofitting old ones on total residential energy consumption rates can be calculated from Eq. (2a) or (2b); the results are shown in Figure 10 for $\frac{e_2}{e_1} = 0.50$.* As expected, with a zero retrofit rate the reduction in annual energy growth rate is modest, from 5% per year to about 4% per year for $t > 6$. Since the residential sector consumes about 22% of all primary energy, this reduction amounts to a reduction of about 0.22% per year in total primary energy growth rate.

However, if a retrofit rate of 2% per year could be achieved (for example), a reduction in growth rate in annual energy consumption in the residential sector from 5% per year to about 3% per year would occur, and this slowdown would account for a corresponding reduciton of about 0.4% per year in the growth rate for total primary energy. When combined with the introduction of efficient vehicles utilizing about 60% of the gasoline per mile that standard vehicles require (Section 2), the two components of an energy-conserving strategy taken together would bring the growth rate in the U.S. primary energy down from 4.2% per year to about 2.8% per year in the crucial time period $6 \leqslant t \leqslant 12$.

* According to Reference 3 values of $\frac{e_2}{e_1} = 0.50$ are achievable even with the application of present technology.

4. Implications of a Slowdown in the Rate of Growth of U. S. Energy Demand

4.1 Implications for Energy Imports and Domestic Energy Supplies

As shown by the highly simplified examples discussed in Sections 2 and 3, a reduction of 1.2% – 1.4% per year in the annual growth rate of U. S. energy demand is achievable by 1985, considering only space heating and the "automobile" as a total system. Judging by the OEP report[3] an additional reduction of about 0.4% per year in the annual rate of growth of the remaining 50% of U. S. primary energy is attainable by 1985. Thus the overall reduction lies in the range of 1.6% – 1.8% per year; in other words a growth rate in primary energy demand of about 2.5% per year by 1985 is indeed feasible.

The importance of such a slowdown in the rate of growth of energy consumption is graphically illustrated in Figures 11 and 12.* The demand projection labelled Ⓓ represents the NPC "intermediate demand" estimate,[2] based on an annual growth rate of 4.2% in the period 1971-1985, and an annual growth rate of 3.2% in the period 1985-2000.† The domestic energy supply projection labelled Ⓐ follows the NPC's "initial appraisal" of the annual rate of growth of about 2.6% through 1995.+ Obviously imports of primary energy would have to increase very rapidly if the combination ① – Ⓐ were actually to occur, as shown in Figure 12 by the curve so labelled. However, if the annual rate of growth in energy demand were to decrease from 4.2% in 1970 to about 3.5% by 1975, to 2.9% by 1980, to 2.5% by 1985, and to about 2% by 1990 (curve labelled ② in Fig. 11), the predicted time history of U. S. primary energy imports would be fundamentally different, as shown by the curve labelled ② – Ⓐ in Figure 12.‡ Projected energy imports peak in 1985 at a level of about 15% of total U. S. primary energy requirements at that

*For readers accustomed to thinking about energy in other units, please note that 5.9 quadrillion BTU (5.9×10^{15} BTU) are equivalent to one billion (10^9) barrels of oil; *or* 3.6×10^{15} BTU are equivalent to 10^{12} kilowatt hours.

† These figures are qualitatively similar to Figs. 1 and 2 contained in a previous publication by the senior author,[5] except that in Reference 5 the NPC "initial appraisal" demand projection based on an annual growth rate of 4.2% in the period 1971–1985 was extended without change through the period 1985–1995.

+ In the NPC Summary Report[2] this projection lies midway between Case IV (continuation of the present trends) and Intermediate Case III.

‡ Numbers in parenthesis shown in Fig. 12 (e.g., (36)) represent the percentage of total primary energy supplied by imports.

time, or at a level about 60% higher than the current (1973) volume of energy imports. Moreover, increases in the rate of domestic supply of energy (curve labelled Ⓑ in Figs. 11 and 12) have a much larger relative effect than if the demand curve ① is followed. This simple illustration reminds us once again that a small difference between two large numbers is very sensitive to modest changes in either of these two numbers.*

Although strenuous efforts and important policy changes are needed in order to increase domestic energy supplies, the annual rate of increase required by curves Ⓐ or Ⓑ in Figure 11 is close to the intermediate supply Case III analyzed in the NPC study,[2] rather than the "high" supply Case I. In view of environmental, land use, capital investment and technical and logistical constraints, Case III is regarded by the authors of the NPC report as much more realistic than the "high" supply Case I. For example, the cumulative capital investment required by Case III is about 265 billion dollars (exclusive of electricity generation and transmission) in the period 1971-1985, as compared to 311 billion dollars required by Case I.

However the domestic energy supply "mix" may be somewhat different than that envisioned in the NPC study. Even the lowest NPC projection of installed nuclear power electric generating capacity for 1985 of about 240,000 MW(e) is probably too high by at least 20%, and the "intermediate" estimate of 300,000 MW(e) is too high by about a factor of 1.5. The deficit of about 4 quadrillion BTU's in annual energy supply would have to be made up by a much more rapid build-up of synthetic gas production (for example), as shown in Figure 3 of Reference 5. Such unavoidable uncertainties in estimated demand and domestic supply have large relative effects on required energy imports. Thus it would seem desirable to encourage diversity in domestic energy sources. The cost of this diversity may be less than the cost of increased imports that would be incurred if the available range of domestic energy sources were too narrow, and some of these sources failed to come up to expectation.

* The energy demand projection labelled ② in Fig. 11 lies about 12% below the NPC intermediate estimate[2] for 1985, and about 25% below the NPC intermediate estimate for 1995. Thus, curve ② lies about midway between the OEP demand estimates[3] corresponding to the use of all "mid-term" and all "long-term" energy conservation measures, resp.

4.2 Policy Implications

So much has been written recently about U. S. energy policy that only a few salient points are worth emphasizing here, pertaining especially to a slowdown in the rate of growth of energy demand. These points are concerned mainly with the complementary roles of pricing, taxation, incentives and regulations. These remarks are not meant to be difinitive, but are designed to stimulate discussion of policy alternatives.

Almost all recent energy studies agree that the unit price of energy in all forms is bound to increase substantially (in fixed 1973 dollars) over the next decade or two. But increases in unit prices may not be sufficient to reduce the rate of growth in energy demand in a timely fashion, because they affect operating costs much more strongly than "first costs", and because of well-known time lags in response to price changes. For example, the introduction of "efficient" automobiles at the desired rate (Section 2) might be encouraged not only by the predicted increases in the price of gasoline, but also by a "purchase tax" on passenger automobiles in proportion to their performance in gallons/mile,* and/or by specifications on fuel consumption in conjunciton with regulations on pollutant concentrations in automobile exhaust emissions. A "bonus" or "negative purchase tax" might be awarded to those makes of automobiles that do better than these standards.

Similarly, the desired rate of introduction of energy-conserving living units (Section 3) could be encouraged not only by the predicted increase in unit energy prices, but also by regulations adopted at local state and federal levels on the amounts of building insulation required. As our understanding of energy consumption levels of various building designs improves, these crude regulations might be replaced by regulations and incentives based on overall annual energy consumption in BTU per square foot, leaving the design details up to the ingenuity of architects and builders.

* EPA studies show that an automobile weighing 5000 pounds consumes about twice as much gasoline per mile on the average as an automobile weighing 2500 pounds.

In the next decade, however, even more difficult questions arise, as shown by Figure 2. If the growth rates of 4% per year in *total* automobile population and 1% per year in average mileage driven per vehicle persist, then the annual rate of energy consumption by automobiles begins to increase again after the tenth year, even if no new "standard" vehicles are produced after that year. The recent rapid growth in the number of "recreational vehicles" in the U. S. shows that a reliance on "saturation" to reduce these growth rates may prove to be illusory. In addition to pricing, taxation and regulation, it will probably be necessary to plan in the long run ($t \geqslant$ 10-12 years) for cities and towns in which energy-consumption is a primary consideration. Distances from home to work, shopping and recreation would be minimized, multi-passenger vehicles utilized wherever possible, and all structures would be designed to certain energy consumption specifications.

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Figure 1
AUTOMOBILE POPULATION HISTORY CASE 1 AND 2

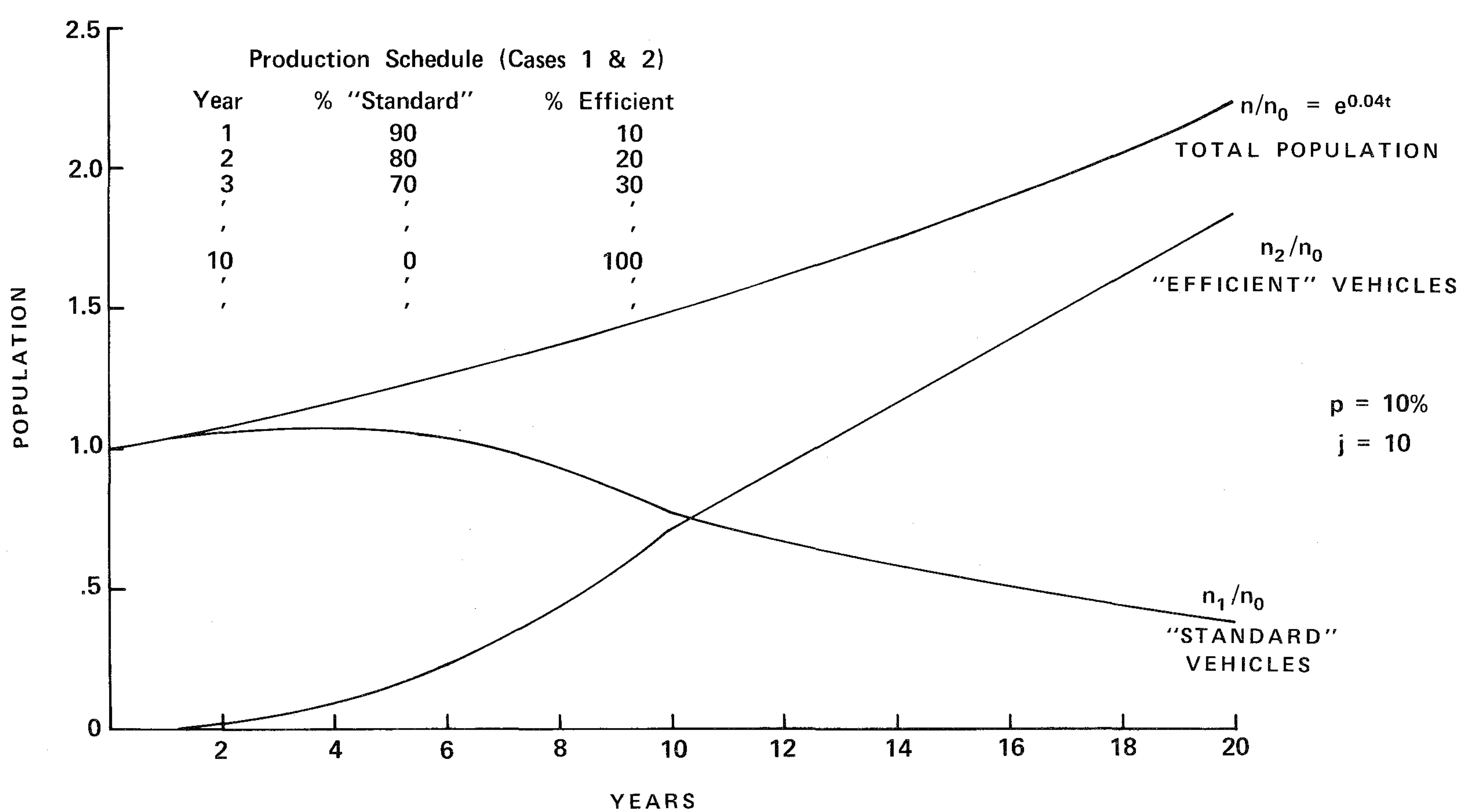


Figure 2
ENERGY CONSUMPTION BY AUTOMOBILES CASE 1

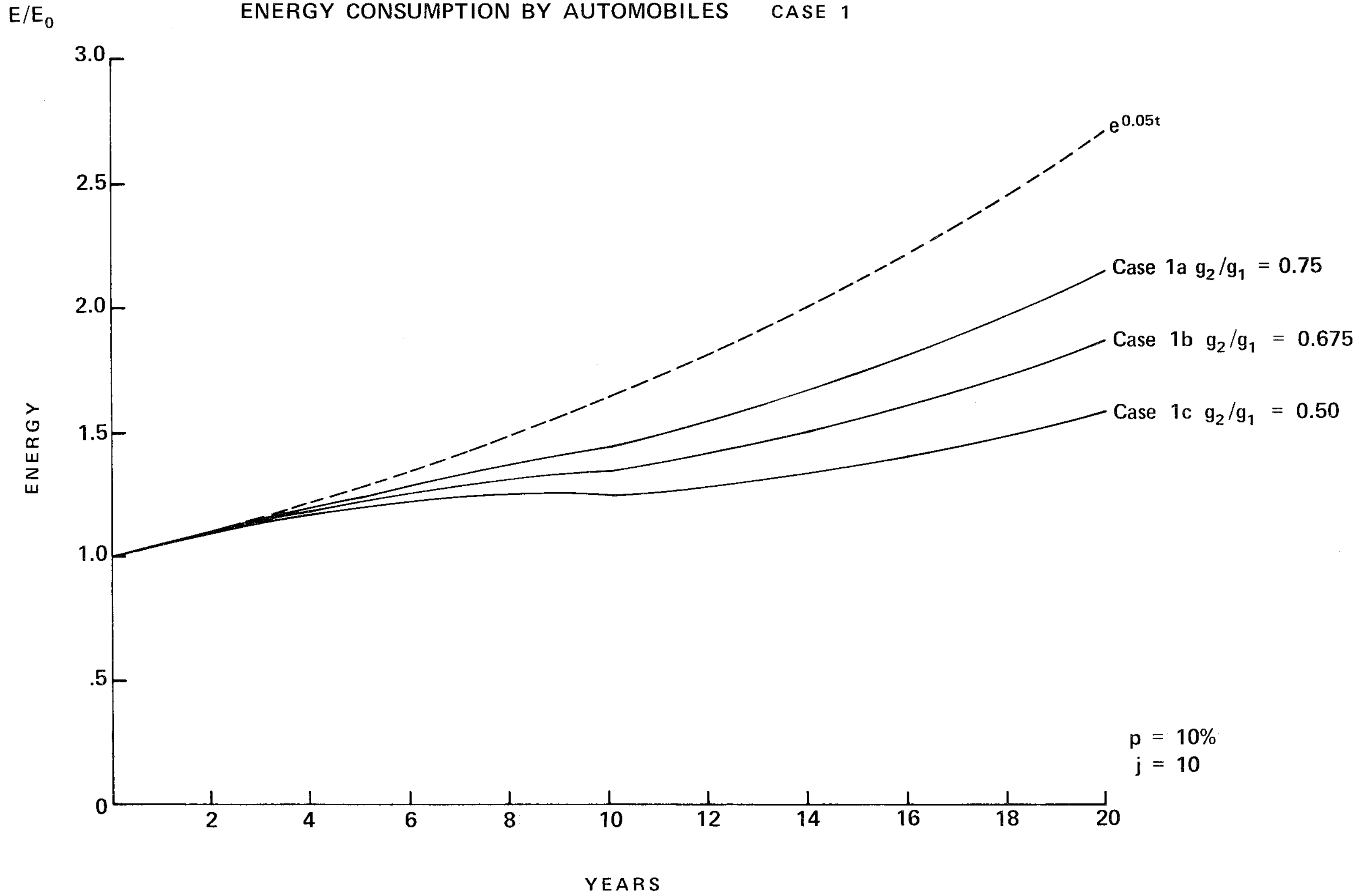


Figure 3
ENERGY CONSUMPTION BY AUTOMOBILES CASE 2

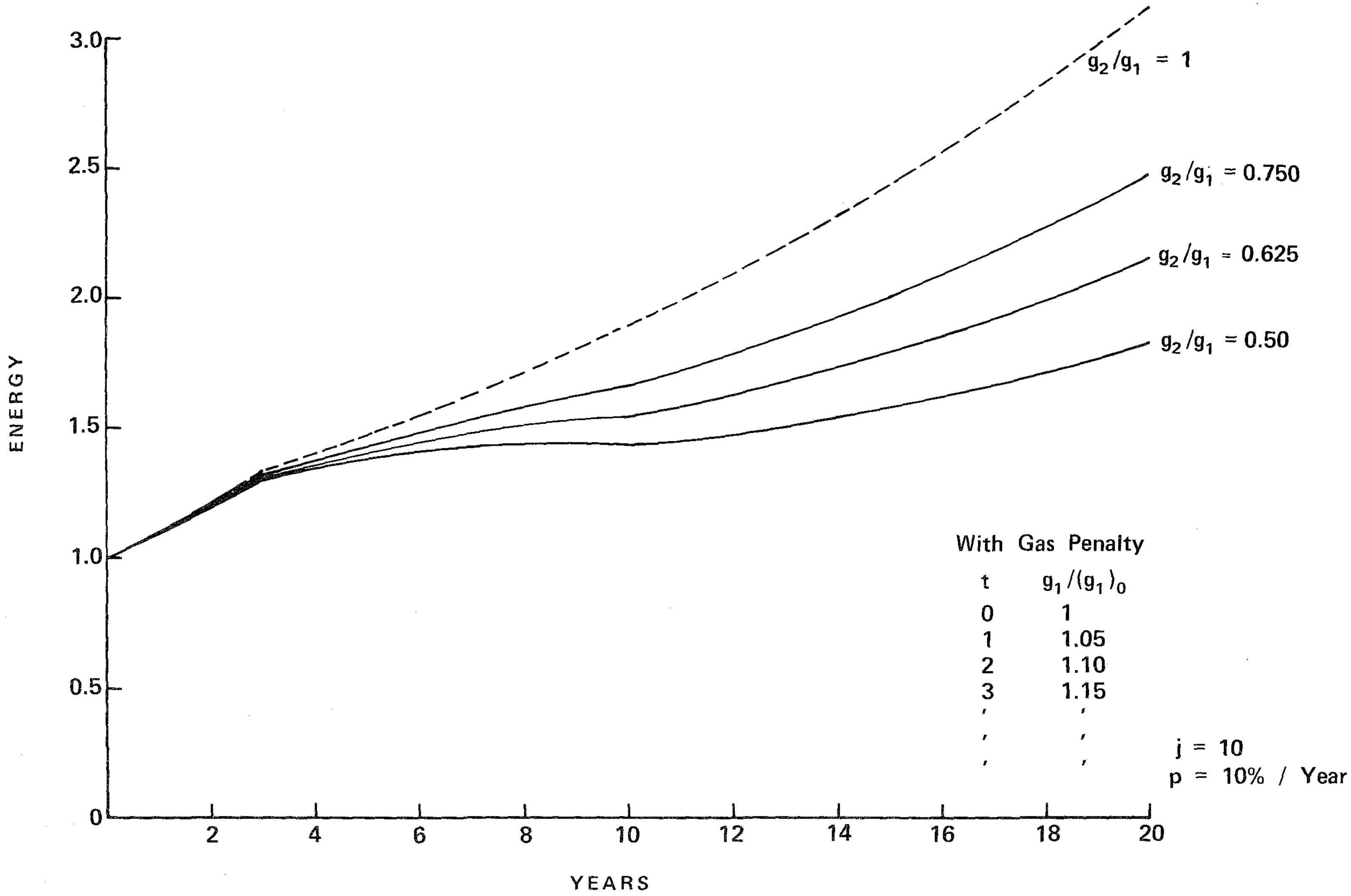


Figure 4
ENERGY CONSUMPTION BY AUTOMOBILES
COMPARISON OF CASES 1c and 2c

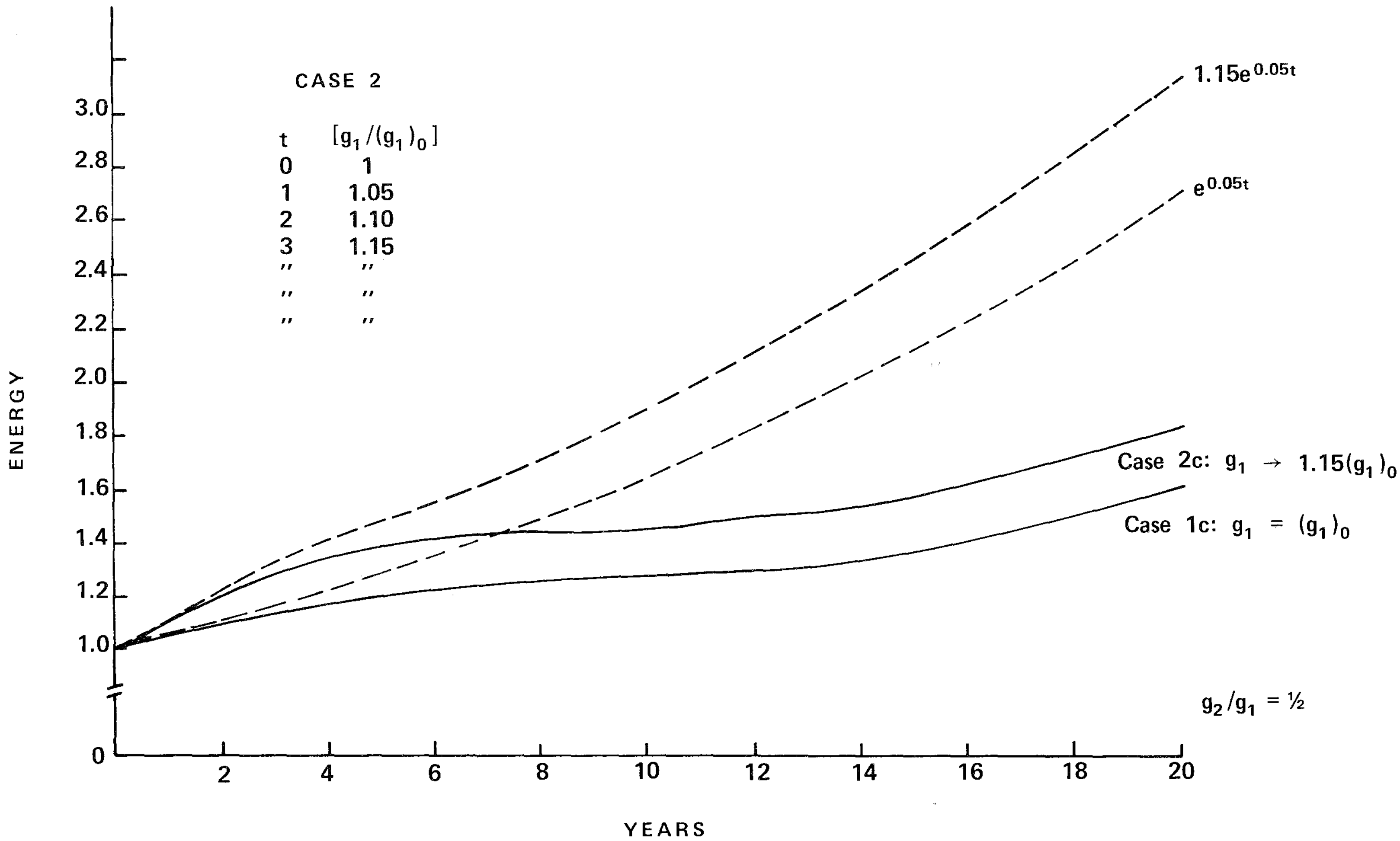


Figure 5
AUTOMOBILE POPULATION HISTORY CASE 3

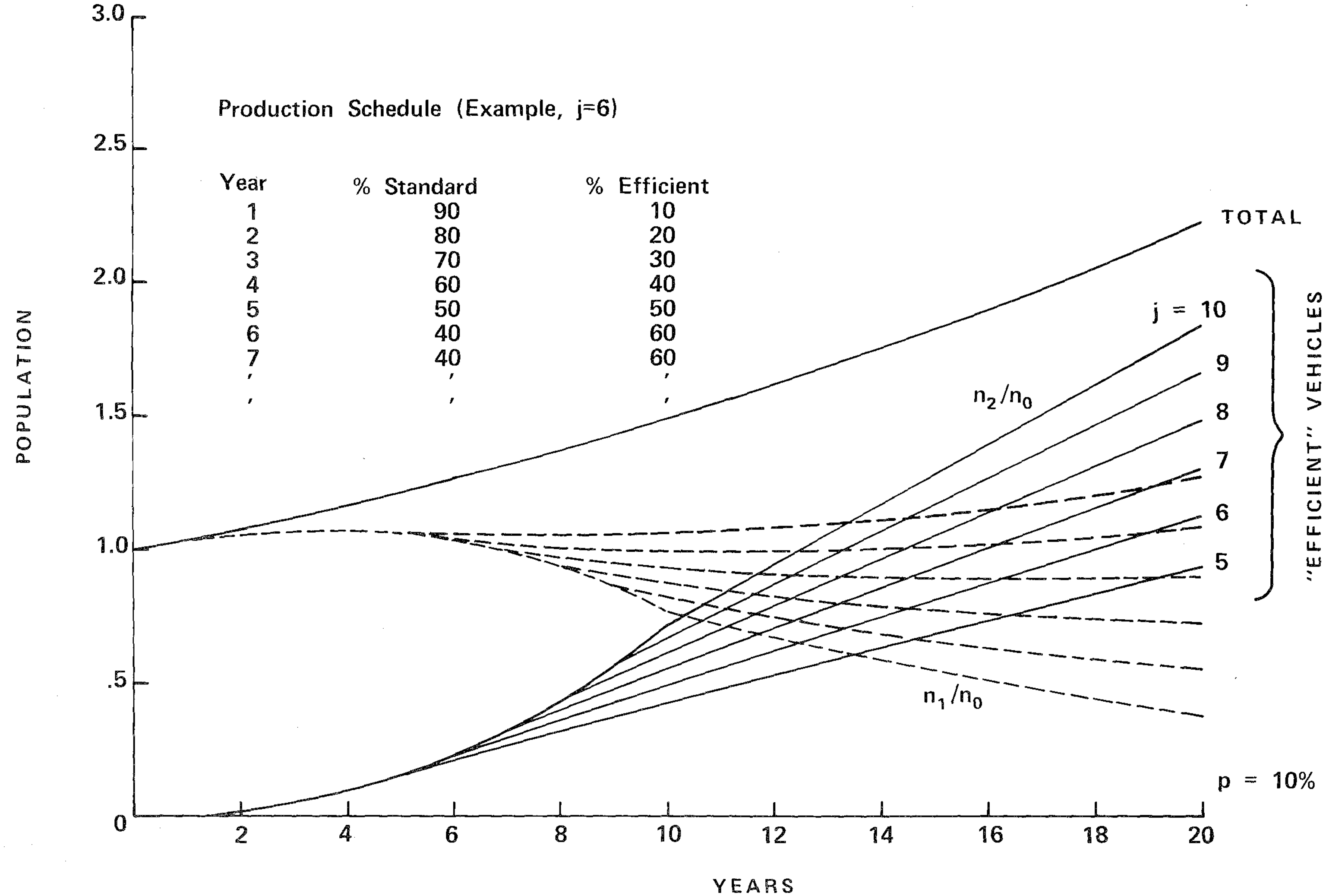


Figure 6
ENERGY CONSUMED BY AUTOMOBILES CASE 3

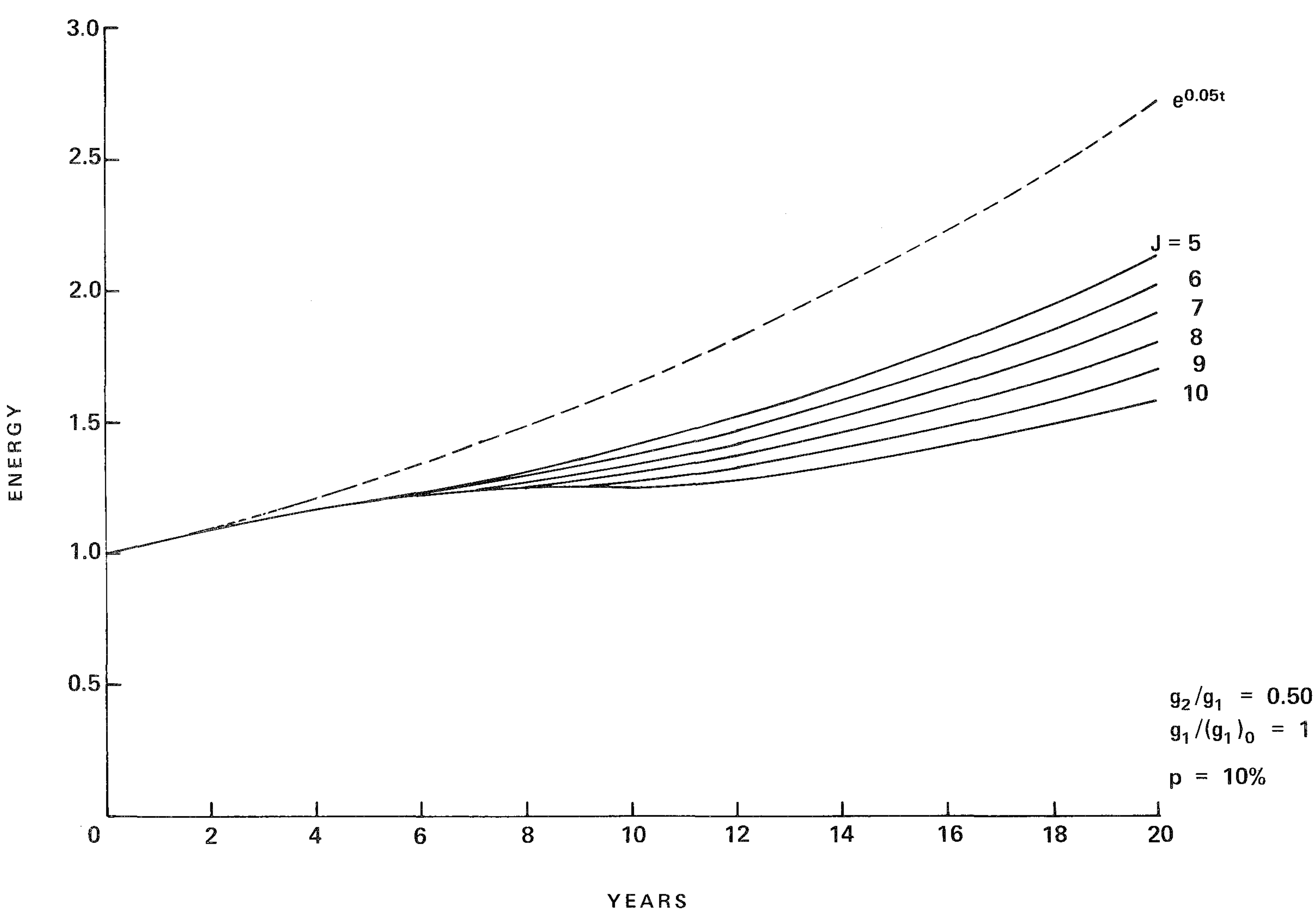


Figure 7
AUTOMOBILE POPULATION HISTORY CASE 4

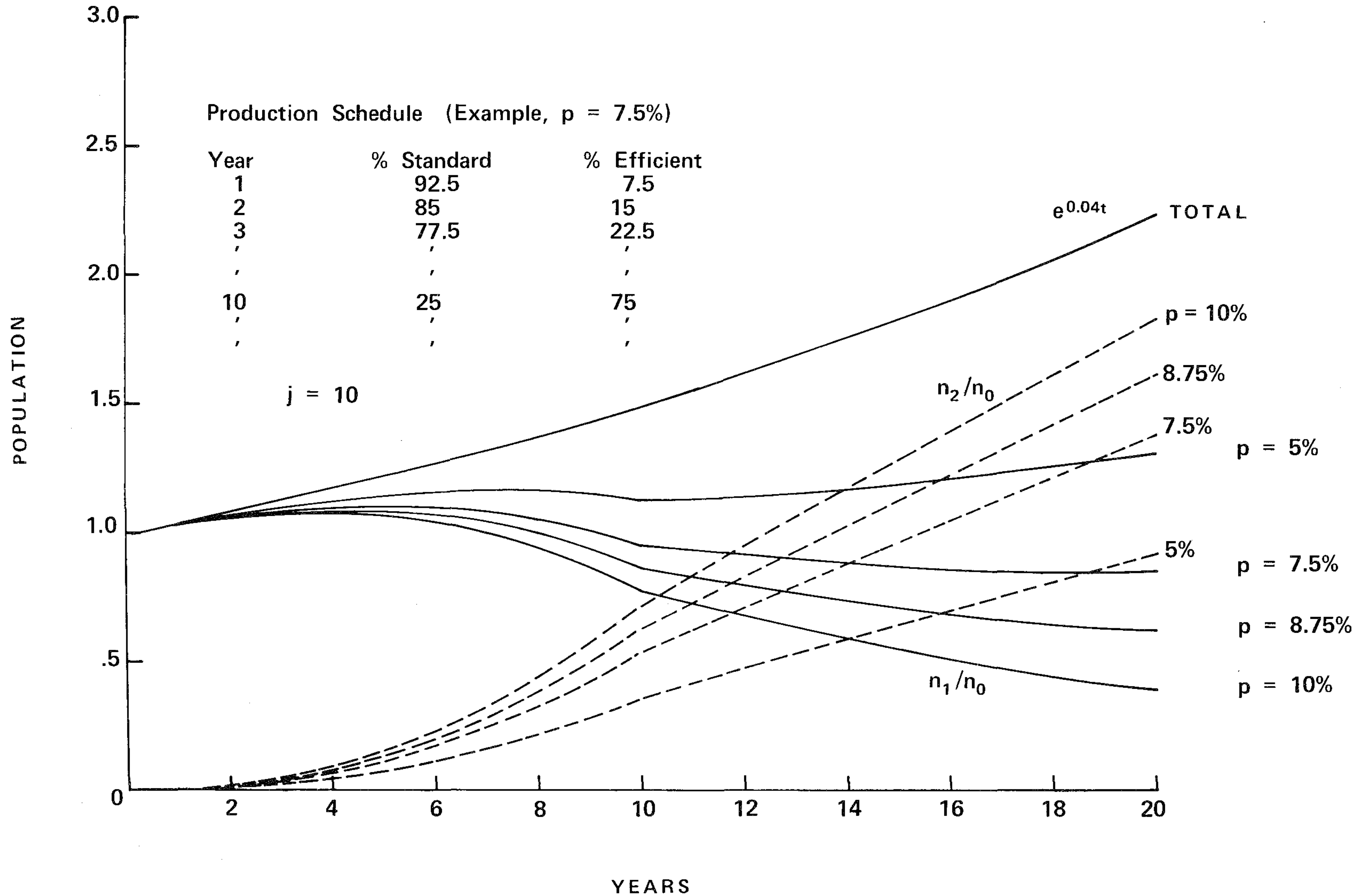
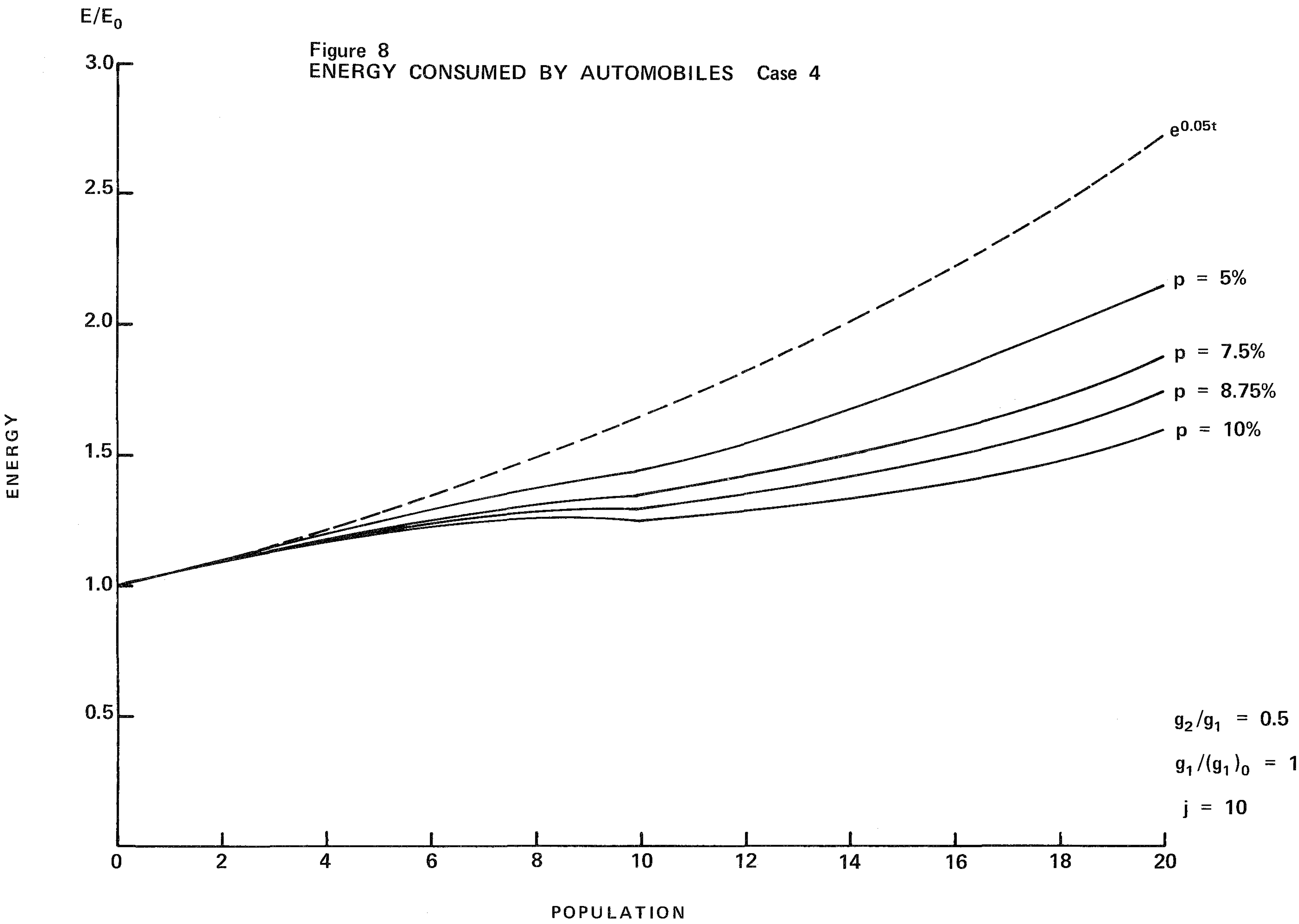


Figure 8
ENERGY CONSUMED BY AUTOMOBILES Case 4



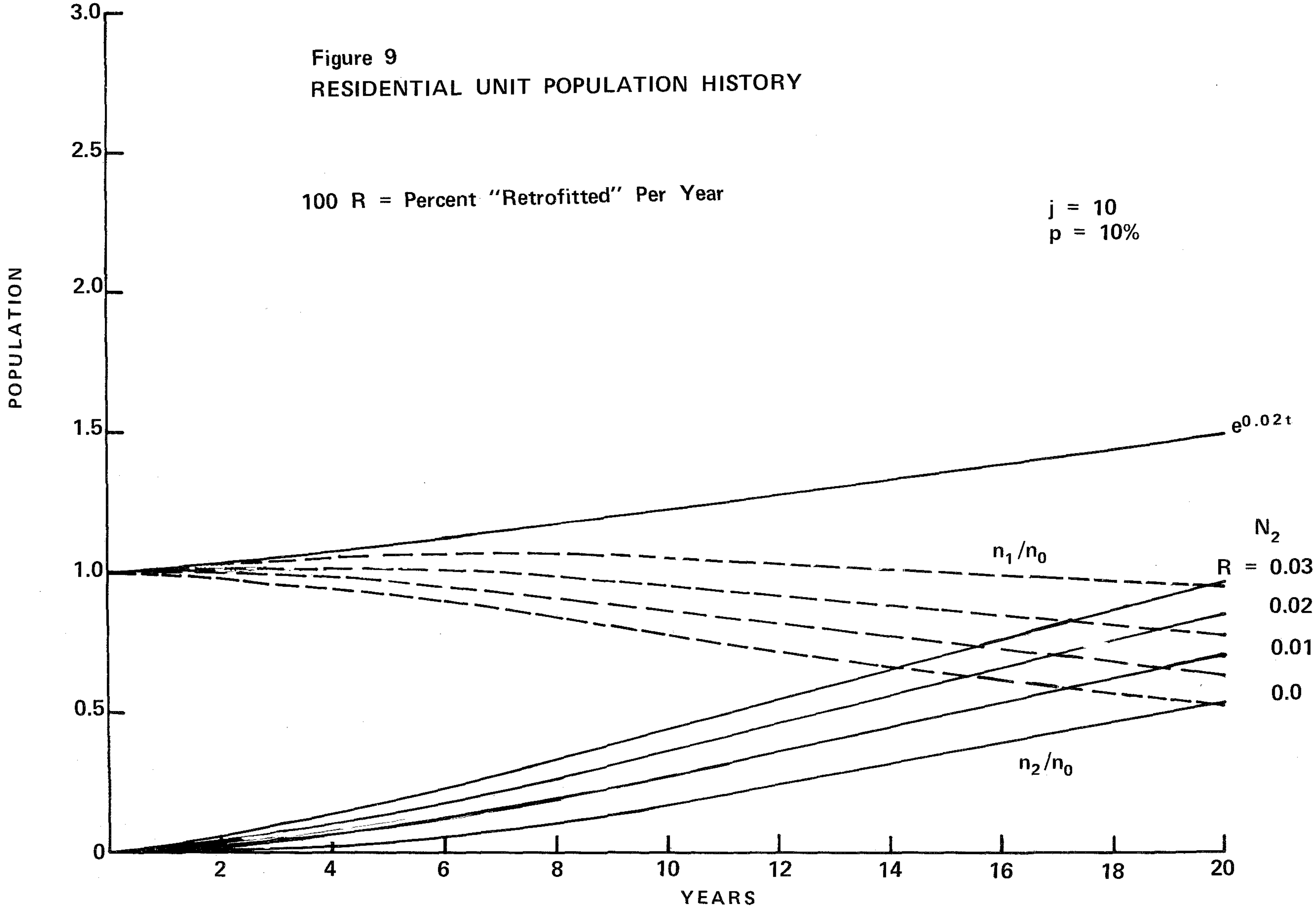


Figure 9
RESIDENTIAL UNIT POPULATION HISTORY

Figure 10
ENERGY CONSUMED BY RESIDENTIAL UNITS

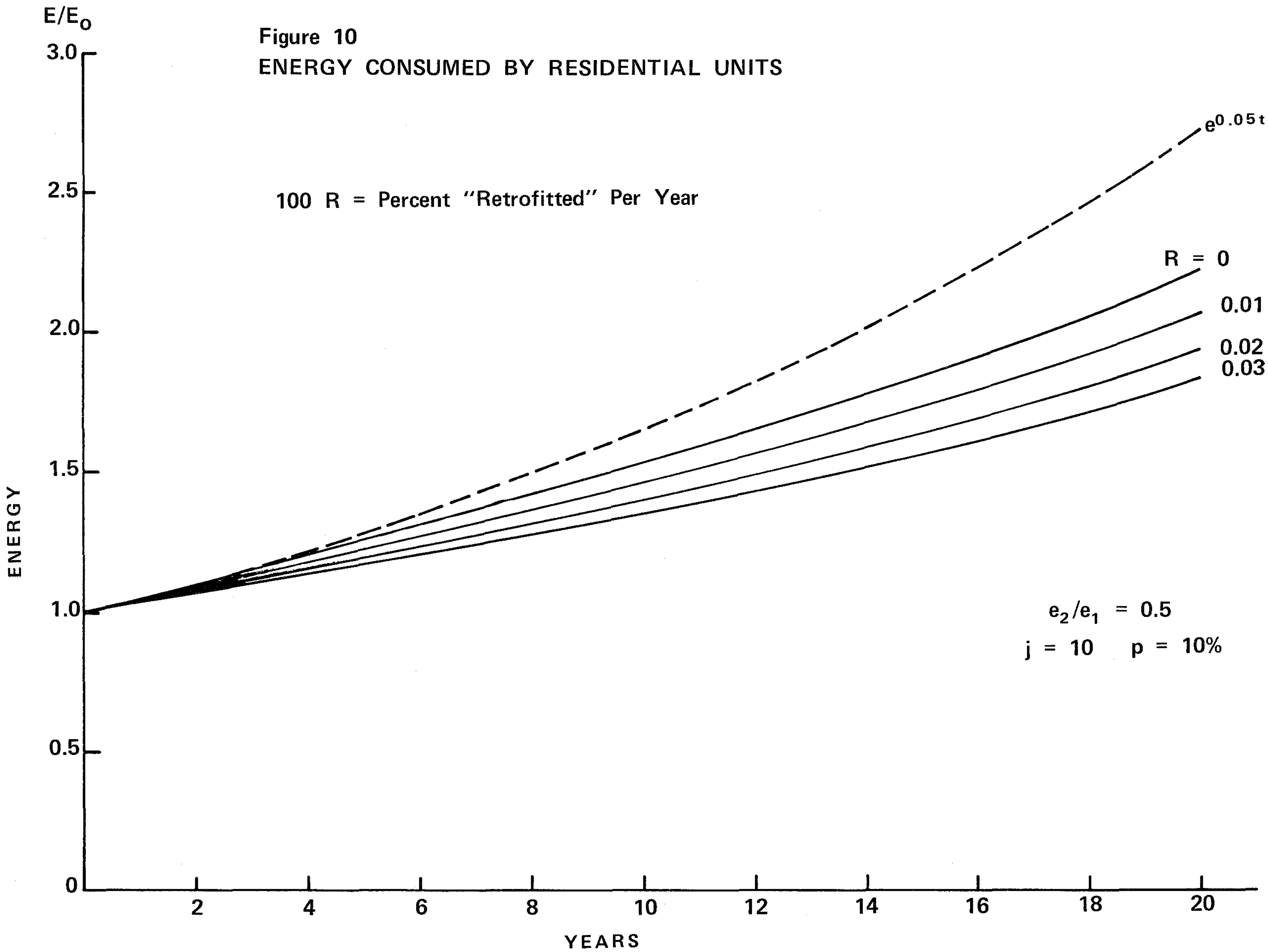


Figure 11
ANNUAL U.S. PRIMARY ENERGY DEMAND AND DOMESTIC SUPPLY – TWO PROJECTIONS

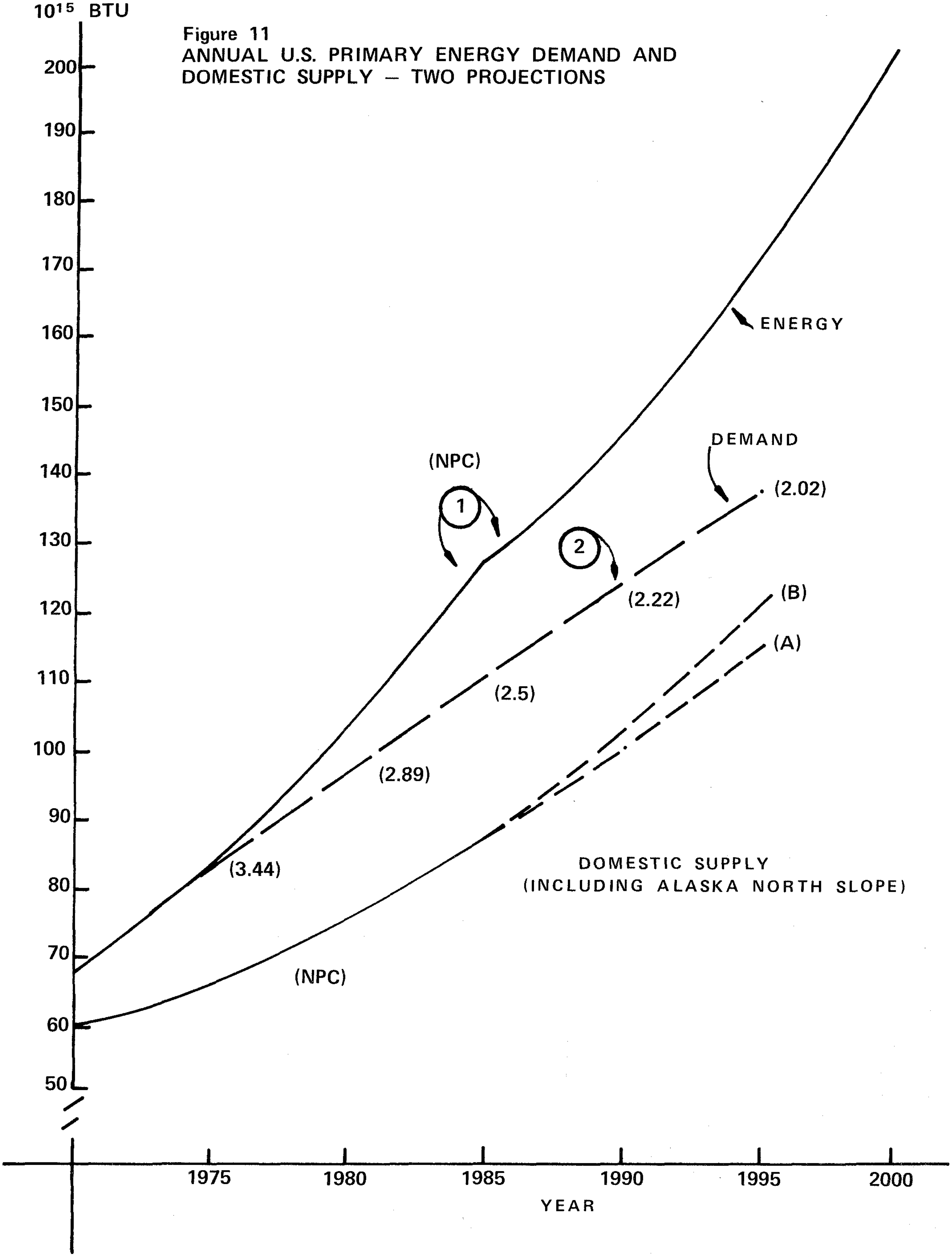
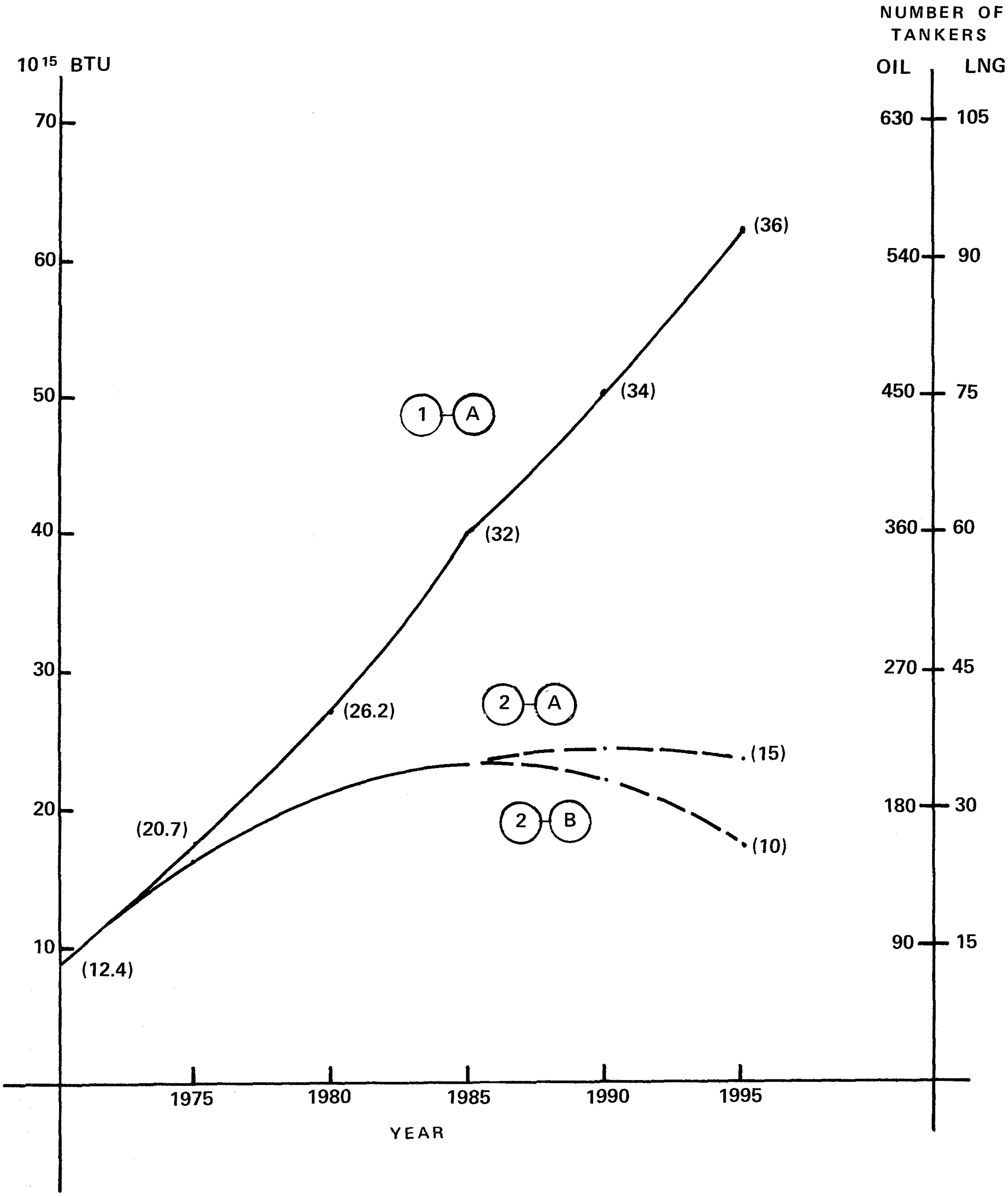


Figure 12
ANNUAL U.S. PRIMARY ENERGY IMPORTS AND TOTAL NUMBER OF TANKERS REQUIRED (250,000 DWT) THREE PROJECTIONS



APPENDIX

A.1 Automobile Population History

Phase 1: $0 \leqslant t \leqslant j$

During this phase the differential equations describing the time history of the automobile population are as follows:

$$\begin{aligned} & & &\text{BIRTH RATE} & & \text{DEATH RATE} & \\ \frac{dn_1}{dt} &= & & b(1 - p't)n & - & \; d \cdot n & \qquad \text{(A–1)} \\ \frac{dn_2}{dt} &= & & (bp't)n & - & \; 0 & \end{aligned}$$

and

$$\frac{dn}{dt} = (b - d)n \qquad \text{(A–2)}$$

where $p' = 10^{-2}\ p$

According to the last of this set of equations, when b and d are taken as constants

$$n = n_0 e^{rt} = n_1 + n_2, \text{ where } r = b - d$$

By utilizing this expression for n in the differential equation for n_2, and integrating, one obtains

$$\frac{n_2(t)}{n_0} = \frac{p'b}{r}\left[te^{rt} - \frac{(e^{rt} - 1)}{r}\right] \qquad \text{(A–3)}$$

Also,

$$\frac{n_1}{n_0} = e^{rt} - \frac{n_2}{n_0} \qquad \text{(A–4)}$$

Phase 2:

In Phase 2, $t \geqslant j$, and the birth and death rates of standard and efficient vehicles are "frozen" at their values for $t = j$.

The differential equations for this phase are as follows:

$$\frac{dn_1}{dt} = b(1 - p'j)n - d \cdot n_1$$
$$\frac{dn_2}{dt} = (bp'j)n - d \cdot n_2 \qquad \text{(A–5)}$$

By integrating the differential equation for n_2 (t) one finds that for $t > j$:

$$\frac{n_2(t)}{n_0} = p'j \quad [e^{rt} - e^{(bj-dt)}] + \frac{n_2(j)}{n_0} e^{-d(t-j)} \qquad \text{(A–6)}$$

Also, $$\frac{n_1(t)}{n_0} = e^{rt} - \frac{n_2(t)}{n_0} \qquad \text{(A–7)}$$

In all the calculations for automobiles made in this report b = 0.11 and d = 0.07.

When the birth and death rates are taken as constants, as in the present analysis, the governing parameters in Phase 1 ($0 \leqslant t \leqslant j$) are $\frac{pb}{b-d}$ (b–d) and j itself, while in Phase 2 the situation is more complicated and the parameters j, p, (b–d) and b, d all enter into the determination of the population history.

A.2 Population History of Residential Units

Phase 1: $0 \leqslant t \leqslant 10$

In this first period,

$$\frac{dn_1}{dt} = b(1 - p't)n - d \cdot n - Rn_1 \qquad \text{(A–7)}$$

$$\frac{dn_2}{dt} = (bp't)n - 0 + Rn_1$$

$$\frac{dn}{dt} = (b - d)n \qquad \text{(A–8)}$$

where 100R is the percentage of existing houses retrofitted each year. Again, $\frac{n}{n_0} = e^{rt}$, where $r = (b - d)$, provided that b and d are assumed to be constants.

By integrating the differential equation for $n_2(t)$ one gets

$$\frac{n_2(t)}{n_0} = \frac{p'b}{r+R}\left[te^{rt} - \frac{(e^{rt} - e^{-Rt})}{r + R}\right] + \left(\frac{R}{r+R}\right)\left[e^{rt} - e^{-Rt}\right] \qquad \text{(A–9)}$$

and

$$\frac{n_1(t)}{n_0} = e^{rt} - \frac{n_2(t)}{n_0} \qquad \text{(A–10)}$$

Phase 2: For $t < 10$, $(1 - 10p') = 0$ in this simple illustrative sample, so

$$\frac{dn_1}{dt} = -(d + R)\, n_1$$

and

$$\frac{n_1(t)}{n_0} = \frac{n_1(10)}{n_0}\, e^{-(d+R)\,(t-10)} \qquad \text{(A–11)}$$

In this report $b = 0.03$ and $d = 0.01$.