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Sensitivity Analysis of the Residential Energy Use Module of the Commercial and Residential Energy Use Emissions Simulation System (CRESS)

L. D. Trowbridge

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ORNL/TM-10478

Engineering Physics and Mathematics Division

SENSITIVITY ANALYSIS OF THE RESIDENTIAL ENERGY USE MODULE OF THE COMMERCIAL AND RESIDENTIAL ENERGY USE EMISSIONS SIMULATION SYSTEM (CRESS)

L. D. Trowbridge

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ABSTRACT

A sensitivity analysis of HOME2, the residential energy use component of Argonne National Laboratory's Commercial and Residential Energy Use and Emissions Simulation (CRESS), has been carried out using an automated sensitivity analysis tool developed at Oak Ridge National Laboratory. HOME2 projects U.S. residential sector energy use from a number of historical and projected economic and demographic parameters. The energy use projections from HOME2 are used in later modules of CRESS to estimate future emissions for five fossil energy-related atmospheric pollutants. Sensitivities of energy use projections to the various driver and control parameters are presented in this report.

Automated sensitivity analysis provides the ability to explore many aspects of model behavior. In the early phases of this study, sensitivity analysis of a predecessor version of HOME2 (June 1986) revealed anomalous behavior in several areas, which led to detection and correction of some difficulties in that version of the residential energy use module of CRESS.

SENSITIVITY ANALYSIS OF THE RESIDENTIAL ENERGY USE MODULE OF THE COMMERCIAL AND RESIDENTIAL ENERGY USE EMISSIONS SIMULATION SYSTEM (CRESS)

I. INTRODUCTION

CRESS, the Commercial and Residential Energy Use and Emissions Simulation System,[1] models the emissions of five atmospheric pollutants in the continental United States over the period 1980 to 2030. It is designed to provide the commercial and residential sector emission projections for a more comprehensive set of models sponsored by the National Acid Precipitation Assessment Program (NAPAP). This sensitivity study was undertaken with the support of the Department of Energy's Office of Planning and Environment and is supplementary to the Argonne National Laboratory (ANL) work on CRESS.

The fundamental task of CRESS is to translate projections of future economic, technological, and geographic parameters into projections of pollutant emissions. CRESS consists of a series of five computer programs which perform various components of this task. The five programs and their basic functions are:

PREP.FOR	Restructure input data sets
HOME2.FOR	Residential Sector Energy Use projections
CSEM2.FOR	Commercial Sector Energy Use projections
REGION.FOR	Disaggregate HOME2 and CSEM2 output by state
MODEL6.FOR	Project pollutant emissions from energy use and 1980 pollution data

The main computational work of the CRESS system is done in the HOME2, CSEM2 and MODEL6 modules. Sensitivity analyses have been conducted on these three modules separately. Earlier reports[2,3] detail the analyses of the emission and commercial sector modules. This report will concern itself with the residential sector module, HOME2. The purpose of this work is to determine the responses of HOME2 to its various inputs and control

parameters. This should be of benefit in several ways. It will highlight those factors which are of relatively more importance in determining the model's output, and which are of less importance. To the user of the model, this study should aid in the understanding of how the model is likely to behave; to the developers of the model, this may help determine whether the model functions as intended. Indeed, the latter has already occurred in that anomalous behavior detected in the earlier (June 1986) version of HOME2 led to development of the current version. The sensitivity values presented are also of use in propagating sensitivity and possibly uncertainty through the CRESS system as a whole.

II. CRESS BACKGROUND

The CRESS system consists of 5 separate FORTRAN programs and 42 input data files containing on the order of 200,000 data elements. The system produces one permanent and 6 temporary output files. The full CRESS system can be conceptually divided into 5 separate modules, each consisting of a single program and its associated input and output files. For the purposes of using Oak Ridge National Laboratory's (ORNL) automated sensitivity analysis system (named GRESS[4]), this separation is necessary. Automated coupling of sensitivities between program modules is under development, but at present must be done manually. This paper will discuss sensitivities in the residential sector energy use module, HOME2.FOR, on a stand-alone basis. The projections generated by HOME2, along with parallel projections from the commercial sector energy use module, CSEM2, are used in the emission module to forecast pollutant emissions. Sensitivities derived from these studies can be used to estimate the response of CRESS as a whole to its overall inputs.

The CRESS programs were run at ANL on an IBM 3033 system. While IBM 3033's are available at ORNL, for logistic reasons (cost, turnaround time, and availability of the most recent version of GRESS), the runs at ORNL were conducted on the Scientific and Technical Computing system, which contains a VAX 8600 on which this work was done. Both systems claim to use the same version of FORTRAN, and no compatibility problems were encountered between the two implementations, as far as the HOME2 module is concerned, other than the necessary alteration of the IBM JCL to the corresponding VAX DCL. The CRESS DCL was altered to preserve several intermediate data files which HOME2 uses for input or output, and CRESS was run on the VAX 8600 for the "Reference" growth case (as opposed to the "High" and "Low" growth cases).

The output of HOME2 is written to a file named RESCOMMH.NTM, and consists of projections of annual energy use for 7 fuel categories in each of 4 regions for the period 1980 to 2030. This file is one of the temporary files discarded during normal operation on the IBM system, so the results of a VAX run could not conveniently be compared directly to those of the IBM for this file. The overall CRESS output, however, was compared between the IBM and VAX versions, and agreed within the limitations of FORTRAN single precision accuracy, as described in Ref. 2

HOME2 was adapted from HOME, a model developed and used by the Energy Information Administration.[5] HOME was designed to provide intermediate-term (ca 10-year) projections for residential sector energy use and related data for such publications as the Annual Energy Outlook.[6] The ANL adaptation of HOME extends the time horizon to 2030 and makes some minor structural changes to accommodate the needs of CRESS.

HOME is driven by historically determined statistical relationships among a number of input parameters and data sets. The input data include projections of disposable income, housing additions, and fuel prices. Historical data were used to statistically derive values for parameters relating the input projections to internally generated projections of residential housing stock, fuel conversions, and fuel consumption. The details of the HOME design can be found in Ref. 5

It is instructive to compare the HOME2 fuel use projections with similar estimates from other sources. The 1985 NEPP study[7] lists projections for residential sector energy use through 2010. The 1980 and 2010 estimates from NEPP are compared to the HOME2 reference case, which was the basis of this sensitivity study, in Table 1. To illustrate the difference in behavior of the earlier version of HOME2, its projections are also

listed. The current version of HOME2 predicts somewhat lower residential energy use than does the NEPP document; the earlier version of HOME2 had predicted much larger values for overall energy use, largely through overestimate of housing growth.

Table 1. Comparison of HOME2 (6/86 version and current, 5/87, version) output with 1985 NEPP residential energy use projections.[7]

	Residential Energy Use (Quads)					
	1980			2010		
	HOME2 (6/86)	HOME2 (5/87)	NEPP ('85)	HOME2 (6/86)	HOME2 (5/87)	NEPP ('85)
All	9.9	9.9	9.9	15.2	9.2	11.2
Liquids	1.7	1.7	1.7	1.8	0.9	1.2
Gas	4.9	4.9	4.9	6.7	3.7	3.9
Coal	0.06	0.06	0.1	0.04	0.04	0.1
Elec	2.4	2.4	2.4	6.6	3.5	4.3
Renew.	0.8	0.8	0.8	1.2	1.1	1.8

This sensitivity analysis will focus on both the exogenous projections which are intended to drive the model, namely the fuel prices, disposable income, and housing starts, and on the various forecasting coefficients which control and calibrate the model. It is recognized that the values of these forecasting coefficients are correlated, and that a recalibration which would alter the value of one parameter would also alter the values of many others. Such alteration would occur outside the scope of HOME2 (and CRESS). Within the framework of the HOME2 model itself and its existing data, a sensitivity analysis will only examine and reveal those responses which formally exist in an algebraic sense in the code.

HOME2, like many econometric models, uses and projects the time evolution of variables of interest based on their ratios to base year values. For this reason, data arrays which represent the base year values

for variables of interest were not examined. The majority of the parameters examined in this report are read from input files; one was contained within the source code. The variables examined in this study are listed in Table 2.

Table 2. Parameters discussed in this report at varying levels of aggregation. ("Variable" indicates the array name in the HOME2 code; "Description" also includes the implicit or explicit dimensions of the variable array.)

File Name	Variable	Description
RESIN-COEFS.HDDCC819	UBETA	Price & Income Elasticities: ea. (4 Reg x 4 Fuels x 4 End Uses)
	QHDD	Heating Degree Days (4 Reg)
	CGWTH	Coal Use Decline Time Constant
HOUSE.TO81AA15	HDRT	Housing decay rates (4 Reg x 4 Vintages x 2 Classes)
RESEXOG.NTM	PRC	Fuel Price (4 Reg x 6 Fuels x 51 years)
	HINC	Regional Disposable Income (5 Reg x 51 years)
	CON	Housing Starts (5 Reg x 2 Classes x 51 years)
HOME2.FOR	{numeric}	LPG conversion limits for space and water heating

II.1. GRESS

GRESS ("Gradient Enhanced Software System"[4]) is a tool for automating the direct method of sensitivity analysis for FORTRAN programs. It is used as a precompiler on the source code to produce an enhanced source code and library which has the capability of propagating derivatives with respect to any real parameter via the chain rule of differentiation. This enhancement to the original code allows the calculation of the sensitivity

of any variable with respect to any other without (in principle) detailed examination or knowledge of the intermediate processing the code may perform. Multiple sensitivities may be calculated using this tool (limited by computer memory and run time), in contrast to perturbation methods, which generally permit only a single variable to be varied per run. Calculated sensitivities from GRESS are for the particular solution point only; development of a detailed response surface would require rerun of the subject program with altered input values.

Aside from the modification and recompilation required, there is typically a CPU-time penalty associated with running a GRESS-enhanced program. In the case of HOME2, the enhanced version required about 32 times as long (CPU time) to run as the original version. Factors for other programs have ranged from 3 to 50.

Typically, the procedure for utilizing GRESS on an existing model requires modification of the model's source code to solve any incompatibility problems that may exist, precompiling the model through GRESS, and then conducting a limited verification of the GRESS-enhanced version. Compatibility problems proved to be minor. Changes required to HOME2 included replacing quoted strings in data statements with Hollerith format and replacing CHARACTER type declarations with similar length REAL declarations.

The verification step involves two procedures. The first is to confirm that the output results of the GRESS-enhanced version of the program are the same as those of the original model. In this comparison, the results were not identical between the two versions, but none of the numbers output in the file RESCOMMH.NTM differed by more than expected round-off error for single precision FORTRAN.

The second verification procedure requires performing a limited sensitivity study on the original model using a parameter perturbation technique and comparing the resulting response to that calculated using the GRESS-enhanced model. For this test, the sensitivities of 4 output elements with respect to 4 inputs were calculated. The input parameters selected were UBETA(3,1,R,1), a price elasticity for utilization of fuel oil for space heating, one for each of the 4 regions R in HOME2. The 4 output elements were QTAB(3,1,R,11), the corresponding fuel utilization in each of the 4 regions in 1990. The sensitivities for the direct run with perturbed values used a perturbation of approximately 1%. The results of both methods are shown in Table 3. The results of the two methods are in good agreement in all the combinations shown. The utilization for a given region was not influenced by the price elasticity for other regions, giving trivial agreement in that "0 = 0". The non-zero diagonal elements of the tables were also, however, in very good agreement.

Table 3. Comparison of Normalized Sensitivities of Oil Use to Space Heat Price Elasticity: GRESS vs. Perturbation

Sensitivities:	Ubeta dQ / dUbeta Q	Reg 1	Reg 2	Reg 3	Reg 4
GRESS	Reg 1	0.15394	0	0	0
	Reg 2	0	0.18203	0	0
	Reg 3	0	0	0.11900	0
	Reg 4	0	0	0	0.00089
Perturbation = x ca 1.01	Reg 1	0.15416	0	0	0
	Reg 2	0	0.18251	0	0
	Reg 3	0	0	0.11860	0
	Reg 4	0	0	0	0.00083
Unperturbed values:					
QTAB [3,1,Reg,11]:		932.2567	284.2956	164.2791	53.17459
UBETA[3,1,Reg,1] :		-0.9398	-0.9084	-0.5728	-0.0037 (*)

(*) Value #4 was perturbed by 1/37 rather than 1%; sensitivity has been scaled to this value.

In addition to this initial verification, a number of parallel perturbation analyses were carried out during the course of this work to confirm GRESS results, particularly in the early phase of the work (on the June 1986 version of HOME2) when counter-intuitive results were obtained. In all cases, the perturbation results were consistent with the GRESS results.

In addition to compatibility modifications, a modest amount of code must be added to the model to specify parameters of interest and to extract the sensitivities of those parameters to the results of interest. The general techniques and requirements for doing this are discussed and illustrated in Refs. 2 and 4 and will not be repeated. Some discussion is in order, however, regarding tactics used extensively in this study.

Sensitivity coefficients S of a result Q with respect to a parameter P are normalized to their base values (Qo and Po), namely:

$$S = \frac{dQ/Qo}{dP/Po} \quad . \tag{1}$$

The sensitivity coefficient is thus dimensionless. This is a convenient form to study variables whose values change essentially by multiplication or exponentiation, as is the case in HOME2. The sensitivity thus should be interpreted as meaning: "A change of 1% in P will result in a change of S% in Q." The GRESS-calculated results are, however, analytic partial derivatives, and no change in the parameter P is actually made during the calculation of the sensitivity.

HOME2 produces output consisting of projections of fuel use by region, fuel, and year. Since the time-evolution of energy use is the primary theme of HOME2, sensitivities have been calculated for each time period to exhibit the time-evolution of responses of the model.

Input items chosen were those elements intended to drive the model (i.e. those that can reasonably be expected to change from one CRESS run to the next), and also elements that are intended to control the model (i.e. internal parameters which calibrate the response of the functions used to make projections). Both classes of parameters exist in arrays of varying dimensions. For example, the variable array UBETA has 128 elements (2 {price and income} elasticities for {4 fuels} x {4 end-uses} x {4 regions}). The influence of any one member of such an array is likely to be quite small on national totals. For this reason, and in order to limit the number of analyses to a tractable number, most of the responses were calculated by use of aggregation parameters. In this technique, the computer code is modified to multiply each initial definition of a parameter which belongs to the aggregate group by an aggregation parameter which has been given a value of "1.0." Conceptually, for a parameter array, P, the following code would be added:

```
      A = 1.0
      DO 100 I=1,10                                    (2)
  100 P(I) = P(I)*A
```

The sensitivities of the final results are then taken with respect to the aggregation parameter A. The effect is to determine the sensitivities of the results with respect to proportional changes in the magnitudes of the entire aggregate group.

A useful variation of this technique is used to examine the short-term and long-term responses of the model. To examine the short-term response of the model to the parameter P, it would be multiplied by A only in a single time period. The resulting sensitivities emulate the response of the model to a "spike" or "square-wave" perturbation in P. The corresponding long-term behavior can be obtained by multiplying P by the

aggregation parameter in all periods after a certain date. The calculated sensitivities in this case emulate the response to a "shock" or "step-function" perturbation to P. These techniques are very useful in illustrating the sensitivity of the model to time-projections of, for example, fuel price or income.

III. REVISION OF HOME2

The sensitivity analysis of the original (June 1986) version of HOME2 uncovered a number of anomalous response patterns which in turn led to discovery of some errors in the program. HOME2 was revised to produce the current (May 1987) version, on which most of the discussion of this report centers.

Briefly, the most significant error detected in the June 1986 version was traced to a formula which overestimated the housing construction rate. This error was detected by its indirect effect upon the sensitivity of energy use to income elasticity. A second error caused the inadvertent magnification of the response of energy use to changes in disposable income and climate (heating-degree-days). The housing construction rate error and the income response magnification error have been corrected in the current version of HOME2. In a sense, the potential climate response magnification error remains, but the variables which would have to be perturbed in order to elicit this potential error are not readily alterable in the present version. A more complete discussion of this will be given in Chapter 4.

IV. HOME2 - RESULTS

The first class of parameters that will be discussed are the exogenous projections of regional housing starts, disposable income, and prices for 5 fuels. Each projection, read from the file RESEXOG.NTM, contains values for each of four U.S. regions (Northeast, North Central, South, and West) in each year from 1980 to 2030.

IV.1. Price Sensitivities -- PRC

Prices are read into HOME2 each year for each of the four regions in each of six fuel categories: electricity, natural gas, distillate oil, LPG, coal, and kerosene. The coal price, however, is not actually used by the program: energy use is not sensitive to its price.

Price response in HOME2 is intentionally lagged to reflect the slow rate of housing and capital stock replacement. Price sensitivities therefore were examined both for short-term and long-term responsiveness by the method described earlier for sample price excursions beginning in 1990. In all cases, price response has been aggregated across all regions.

Figures 1 through 6 display the sensitivity of fuel use to the price of the indicated fuel in 1990 (i.e. these figures show the response of the model to a short-term price excursion or "spike" in 1990). Figures 1 through 5 display the response of fuel use to price of the five individual fuels mentioned above. For the major fuels (oil, natural gas, and electricity) the sensitivity is fairly small (on the order of 0.1 to 0.2), but persists for many years. The largest effect of price of a particular fuel is to the use of that fuel, as one would expect. Net conservation is reflected in the response of total fuel use (i.e. "All" in the figure keys). In each case, a modest amount of fuel switching is indicated by

the positive response of other fuels. The model contains no overt cross-price elasticities, but accomplishes the indicated fuel switching by equipment conversions and equipment choices for new construction.

LPG use (Fig. 4) rebounds fairly drastically from the pseudo-perturbation to its 1990 price. This behavior was verified by a perturbation run. Similar graphs examining this behavior on a regional basis (not shown) indicate that this rebound phenomenon occurs in all but the Northeast region. Residential use of LPG is not important in CRESS (it is a relatively minor component of energy use in HOME2, and is actually ignored altogether in MODEL6), so this question wasn't pursued. It will later be shown, however, that LPG use is quite sensitive to a limit on its allowable equipment conversions; a reduction in 1990 utilization may have some interaction with this.

Kerosene's price has a very small effect on fuel use. Kerosene is considered internally in HOME2, but is not retained in any of the fuel use categories of the program's output. The influence of its price is felt only through the use of wood: wood responds to the average usage of all fuels, of which kerosene is a minor component (Fig. 5).

Figure 6 displays the sensitivity of fuel use to the price of all fuels (i.e. the response of the model to a general price spike in 1990). In this chart, all fuel prices effectively increase by the same proportional amount, so that all price ratios will remain the same, and fuel switching based on relative price changes will be eliminated (fuel switching occurs through two mechanisms: fuel conversions in existing housing and fuel choice for new construction). The remaining response is the inherent price-induced fuel conservation. The major fuels respond to price in an intuitive manner.

Wood has no inherent price, but responds to average (non-wood) fuel usage, moving in the opposite direction from that of general fuel usage. Thus when prices increase, major fuel usage will decrease and wood will increase in response. Total fuel use, which contains positive contributions from wood and LPG, actually increases very slightly in the long run in response to a temporary price increase.

Long-term price response was examined by calculating sensitivity of use to all prices in or after 1990. Figures 7 through 12 thus display the equivalent of a response to a step increase in price in 1990. The response to most individual fuel prices (Figs. 7-10) slowly grows to reach substantial values by 2030, on the order of -0.4 for gas and electricity, and -1.8 for oil. Kerosene again has little influence on fuel prices (Fig. 11).

A discontinuity appears in the price responses of oil and gas (Figs. 7 and 8), namely a sudden reduction in sensitivity in the year 2019. This is due to price-influenced equipment conversions. The oil- to-gas conversions end for some of the housing categories in the year 2019. In the scenario examined, all eligible oil-burning equipment has been converted to gas for multiple-family housing of vintages 2 through 4 in the Northeast and North Central regions by the year 2019.

Figure 12 displays the response of the model to a general price increase in 1990 (and thereafter). The long-term sensitivity of fuel use to a general price change is in the range of -0.3. This represents the price-induced conservation modeled by HOME2.

Wood is treated differently from the other fuels in HOME2. Wood is considered to have no inherent price, and its use responds to the average fuel usage: its use thus increases when prices rise. Within the model, there is an upper limit imposed on the annual use of wood. The sensitivity of wood to fuel prices decreases in the later periods of the model

because wood use approaches this limit, and the limit becomes the dominant factor in determining use.

Overall, the price responses of HOME2 reflect its intent and design, as reflected in the documentation.[1,5] Price response occurs fairly slowly, as dictated by the price lag parameter. The short-term response to a temporary price fluctuation is small (but persistent), while the long-term response to a continuing price increase is substantial.

IV.2. Population

Unlike CSEM2 and MODEL6 (the commercial and emissions modules of CRESS), population figures are not directly read into or used by HOME2. Implicitly, the housing construction rates and regional disposable income projections, which are exogenous to CRESS, depend on population. There is, however, no formal algebraic relationship between population and energy use within HOME2.

IV.3. Disposable Income

Disposable income is used in a manner similar to fuel price to estimate energy use per house. In the original version of HOME, income response was inadvertently magnified and lagged by the price lag parameter, as had been mentioned above. In HOME2, this has been corrected. The income response, like price response, is lagged, but is of the intended magnitude.

Income shows marked regional differences in its influence on energy use projections. Figure 13 displays the sensitivity of total regional fuel use to post-1989 regional disposable income (i.e. the equivalent of the effect of a permanent income increase in 1990). The sensitivities for total fuel use are fairly low, ranging from a low in the South of around

0.03 to a high (in the Northeast) of about 0.12. These sensitivities are directly due to the values of the UBETA array.

Figure 14 illustrates the effect on national fuel use of disposable income. When the sensitivities are aggregated across all building types and regions, the response of fuel use to income is significant in magnitude and fairly uniform among the major fuel categories, all values being within the range 0.07 to 0.10. In a study not shown, however, moderate regional differences were evident in the sensitivity of specific fuel categories to income.

IV.4. Heating Degree Days (QHDD)

Heating-Degree-days data are used in a manner similar to fuel price and income to estimate space heat energy use per house. Like income, projections of future climate are used with an elasticity array to project climate-response. Historical values are used for the first 4 years of the model (1980-1983); projected values of heating-degree-days for all years past 1983 use the 1983 values.

The climate response of HOME2 is somewhat anomalous in two ways: the response is lagged, and the magnitude of the response is magnified over what is probably the design intent. These effects are illustrated in Figs. 15 and 16. In Fig. 15, the response of the various fuel uses to the value of the 1983 heating-degree-day variable (aggregated over all four regions) is displayed. The intended response to QHDD for a single year (Ref. 5) is that of the one-year response in Fig. 15 (i.e. the sensitivities should be on the order of 0.4 to 0.6). The long-term response to the 1983 QHDD value grows to become much higher, however, because of the way that the climate variable is incorporated into HOME2 (and indeed the HOME model from which it was derived[5]).

Space heat utilization is calculated by the following formula:

$$\frac{U(t)}{U(t-1)} = \left(\frac{P(t)}{P(t-1)}\right)^{Ep} \left(\frac{U(t-1)}{U(t-2)}\right)^{(1-Fl)} \left(\frac{I(t)}{I(t-1)}\right)^{Ei} \left(\frac{H(t)}{H(t-1)}\right)^{Eh} \quad . \qquad (3)$$

where U, P, I, and H are utilization, fuel price, income, and heating-degree days, respectively, t is the time period index, Ep, Ei, and Eh are elasticities for price, income and heating-degree-days, and Fl is a lag parameter whose value is 0.2. The documentation for HOME[5] suggests that heating-degree-days should evoke only an immediate response. Price on the other hand, is intended to be lagged. In the above formula, the price and income elasticities represent the short-term values, and the term in (U(t-1)/U(t-2)) imposes a lag on the long-term price response. In the process, the effective long-term elasticity becomes:

$$E(\text{long-term}) = E(\text{short-term}) \;/\; Fl \quad . \qquad (4)$$

As the value of the lag parameter Fl is 0.2, the long-run response to price, income, and climate will be 5 times the short-run (i.e. single period) response. This lag and magnification effect also operates on the climate term -- its long-run response is also magnified by a factor of 5 over the (intended) short-run response.

In the long-run, the data from only two time periods have a significant influence on the model result. As illustrated in Fig. 16, there is no response to QHDD until 1983, even for values from 1980-1982. This is because in the early years of the simulation, the utilization values are benchmarked to historical data. The QHDD value for 1983 has a large influence because it also provides the projections for all years from 1983-2030. The other influential data value is that of the second period

(1981), which establishes the "norm" for the climate via its influence on the lag factor denominator (U(t-2), above). In the long run, only the ratio between the second and the last data elements is important.

Lest too much be made of this question, several mitigating factors should be mentioned. The first is that the variable values are historical and unlikely to be changed. To the extent the model provides satisfactory answers, this potential problem is unlikely to be activated. Second, the most plausible user perturbation to the data, that of adding new historical data (1984 and beyond) to the input data file, will have no effect on the model output, as the 1984+ data, while present in the data file, is never read into HOME2. Third, to the extent that the data values used represent true climatic averages, there will be no response to magnify.

The 1980 to 1983 data provide some statistics on variance of QHDD over time. The uncertainty in climate can be propagated through the model to estimate the climate-induced uncertainty in energy use, on the assumption that the model behaves linearly in QHDD. The standard deviation of the 1980 to 1983 QHDD is about 3% of their average values. Assuming this represents the uncertainty in the 1983 data relative to the "true" (but unknown) long-term future average for QHDD, the long-term total fuel use projections will be uncertain by 1.2 x 3% = 3.6% due to this factor. This is not a particularly large uncertainty relative to, say, projections of fuel prices.

IV.5. Housing Construction

Housing stock is an important internal parameter of HOME2, in that most of the calculations estimate fuel use on a per-house basis. Regional and national use is later computed by multiplying by housing stock. Initial housing stocks are read from historical data, and exogenous

projections of housing starts are read for each region from the file RESEXOG.NTM. Housing stocks are also subject to attrition via the parameter array HDRT (housing decay rate, with values around 2%/year):

$$\text{Stock}(t+1) = \text{Stock}(t) \times (1 - \text{Attrition}) + \text{Completions} \quad , \qquad (5)$$

where completions are calculated from the exogenous projections of housing starts.

The sensitivity of energy use to housing construction rate is illustrated in Figs. 17 and 18. In Fig. 17 regional housing start values have been aggregated over all years to depict the influence of the housing start rate. In Fig. 18, the regional rates from the year 1990 have been used as parameters. This figure illustrates the influence of a single year's housing construction through time. These two figures indicate that the effect starts in any individual year is minimal, but that the cumulative effect over long periods of time is substantial.

IV.6. Housing Decay Rate

The attrition of housing is depicted by the array HDRT (housing decay rate). Separate values are provided for each decade. The influence of the individual decay rates build during the decade in which they operate, then slowly decline, as illustrated by Fig. 19. Typical attrition rates are in the vicinity of 2% per year. Sensitivity of fuel use to HDRT is not large: -0.04 to -0.08 for "All fuel" use to any particular decade's values. The aggregated effect of all decay rates by 2030 increases in magnitude to -0.29.

IV.7. Minor Parameters

IV.7.A. Utilization Growth Limits. Fuel utilization changes for LPG are limited in the space heat and water heat end-use categories to 5% per

year. The value of this limit was treated as a parameter and the sensitivity of fuel use with respect to the limit was examined. Only the space heat factor had an influence: presumably the water heat limit was never invoked. The sensitivity of LPG use to the space heat growth limit was very high, peaking at ca. 7 (see Fig 20). Partly this is due to the manner of defining the limit parameter: the sensitivity was calculated with respect to the factor "1.05" and not the ".05" part. If the parameter had been defined as the ".05" part of the limit, the result presumably would have been 1/21 as large (i.e. ca. 0.33), which still represents a substantial influence on LPG use.

IV.7.B. Coal Growth (CGWTH). CGWTH is the only parameter that effects coal use, which is projected via an exponential formula:

$$\frac{Q(t)}{Q('80)} = \exp(CGWTH \times t) \quad . \tag{6}$$

The value of CGWTH is about -0.02, and thus the sensitivity of utilization is negative to a magnitude increase in this parameter, growing linearly in time, as shown in Fig. 21. The effect on total fuel use is very small (note that in Fig. 21, the sensitivity of "all fuel use" is magnified by a factor of 100).

IV.8. Price and Income Elasticities - (UBETA)

Price and income elasticities influence the calculation of energy utilization per the equation listed in the heating-degree-day section, above. There are separate values for each of four fuels (oil, gas, electricity, and LPG) in each of four end-uses (space heat, water heat, air conditioning, and other uses) in each of the four regions (northeast, north

central, south, and west). Figures 22 through 25 illustrate the influence of aggregated sets of these elasticities on energy use. Figure 22 depicts the response of the several fuel categories to price elasticity, aggregated over all regions and end-uses. Oil and LPG use would increase in the early years, as their prices are declining during that period. Beyond 1990, all prices are rising in the exogenously supplied price data, so an increase in price elasticity would decrease use. The magnitude of the decrease is dependent on the relative price increase during the model's 50-year time frame. By 2030, The response to oil and gas values are comparable at about -0.3, and electricity is somewhat less at -0.1. LPG's response is somewhat larger at -0.8

Figure 23 illustrates the differences in response by end-use category. Total fuel use is most sensitive to the space heat utilization price elasticities. The other end-use contributions are comparable in size and an order of magnitude smaller than space heat.

Figures 24 and 25 display the income elasticity counterparts to the two previous figures. The influence of income elasticity in general is somewhat smaller than that of price elasticity, growing by 2030 to the order of 0.05 to 0.07. Oil, gas, and electricity use all have similar responses. As in the price elasticity example, space heat income elasticities make the largest contribution to the influence on energy use, though not in as striking a manner.

V. DISCUSSION AND CONCLUSIONS

A sensitivity analysis of the HOME2 component of CRESS has been carried out with the aid of an automated sensitivity analysis tool, GRESS. The automated analysis has assisted in examining and aggregating the extensive quantities of data processed by the model. A sensitivity analysis cannot unaided verify the validity of a model or its input data. As such, this report is not a comprehensive review of HOME2, but should aid such a review by highlighting the responses of HOME2 to its various input and calibration parameters. Ready access to a wide variety of responses in HOME2 (June 1986 version), in fact, lead to detection and correction of errors in that version of CRESS's residential sector component and the generation of the present version.

Within the framework of the model design, sensitivities computed have identified the important contributors to projected residential fuel use, and in particular, have highlighted the time evolution of the responses to influential parameters.

Identification of the "most important" parameters in a model such as HOME2 is somewhat subjective, depending strongly on what one considers to be the primary "result" of the model. Assuming that the model's primary result is identified, importance of a parameter can be gauged by its influence on the result and on its plausible range of values or uncertainty. Only the former (i.e. sensitivity) has been considered in detail in this study. This study has also been restricted in that it examines only the reference economic growth case, and has to some degree aggregated most of the parameters that have been examined.

As the output of this model provides the input to the REGION and eventually MODEL6 components of CRESS, the point of view taken has been to

examine those outputs which will be of most use in evaluating the emission sensitivities in MODEL6. The earlier examination of MODEL6[2] demonstrated that the separate fuel categories differ markedly in their influence on emissions. Since the MODEL6 analysis was conducted on emissions on a national basis, the results from this analysis needed for linkage of sensitivities throughout CRESS are the national energy use projections, categorized by fuel type.

The parameters examined in this study can be categorized into extrinsic projections (fuel prices, population, and disposable income) and intrinsic parameters resulting from judgment or statistical fitting of model equations to historical data. Of the projections intended to drive the model, many can have significant influences on fuel use (i.e. sensitivities range from 0.1 to over 1). Long-term changes tend to have the strongest influences; perturbations of brief duration generally have a minimal influence. This is particularly true for parameters relating to housing stock, namely the housing starts and housing decay rate.

Long-term effects of permanent fuel price changes are significant, with sensitivities (i.e. effectively the long-term elasticity) to a permanent price change eventually growing in magnitude to the order of -0.3 to -1.8. Prices influence fuel use for most of the output fuel categories. The fuels whose prices have a significant influence in important end-use categories are electricity, distillate oil, and natural gas. Kerosene price has minimal influence on the model results, and LPG influences mainly its own use, which happens to be ignored in the emission module of CRESS. Coal is "immune" to prices: its use is projected by a simple declining exponential.

Price responses generally appear sensible and intuitive. A fuel price rise has a depressive effect on that fuel's usage, and smaller

stimulative effect on substitutes. That is, there are both conservation effects and a fuel switching effects. Price-induced fuel switching occurs mainly through fuel conversions.

Short-term response is considerably smaller than long-term. The response of the model to a temporary price change is therefore of less significance than to long-term price changes or to climate and income projections. LPG use exhibits a curious "rebound" in use following the decline induced by a temporary price excursion.

The sensitivity of energy use to income is fairly small (on the order of 0.08), which reflects the regression results from which the original input data for the model were derived.

The response of the model to variations in heating-degree-days is fairly large for two key time periods, probably larger than was intended in the design. As these data are difficult to modify, no immediate problems should arise. To minimize the potential impact of a later model update, however, a minor revision to this section of the code might be considered. An interim measure to minimize the effect of the statistical "noise" in the climate data would be to use long-term average heating-degree-day values for the initial data and for the future projections, rather than data for a single year.

Wood use is treated differently from the major fuels: it responds to average fuel usage, and is thus only indirectly affected by factors driving other fuels. For the most part, these indirect responses are reasonable (e.g. a general fuel price rise will increase the use of wood). In certain cases, however, where general fuel usage increases for other reasons (e.g. increased heating-degree-days), wood will not respond in the intuitive direction.

Many potentially interesting and important relationships are implicit in the input data to HOME2 and to CRESS as a whole and thus will not be revealed by this type of analysis. For example, housing starts are likely influenced by national disposable income. That relationship, however, will not appear in this analysis, or in the analysis of any other part of CRESS, because both housing start and disposable income projections are exogenous to CRESS. The influence of income which is explicitly modeled in HOME2 can, however, be propagated through the emissions module[2] of CRESS to determine its explicit influence on CRESS' emission projections. It is intended that this will be done on completion of the analysis of the three major modules of CRESS (CSEM2, HOME2, and MODEL6), and documented in a later report.

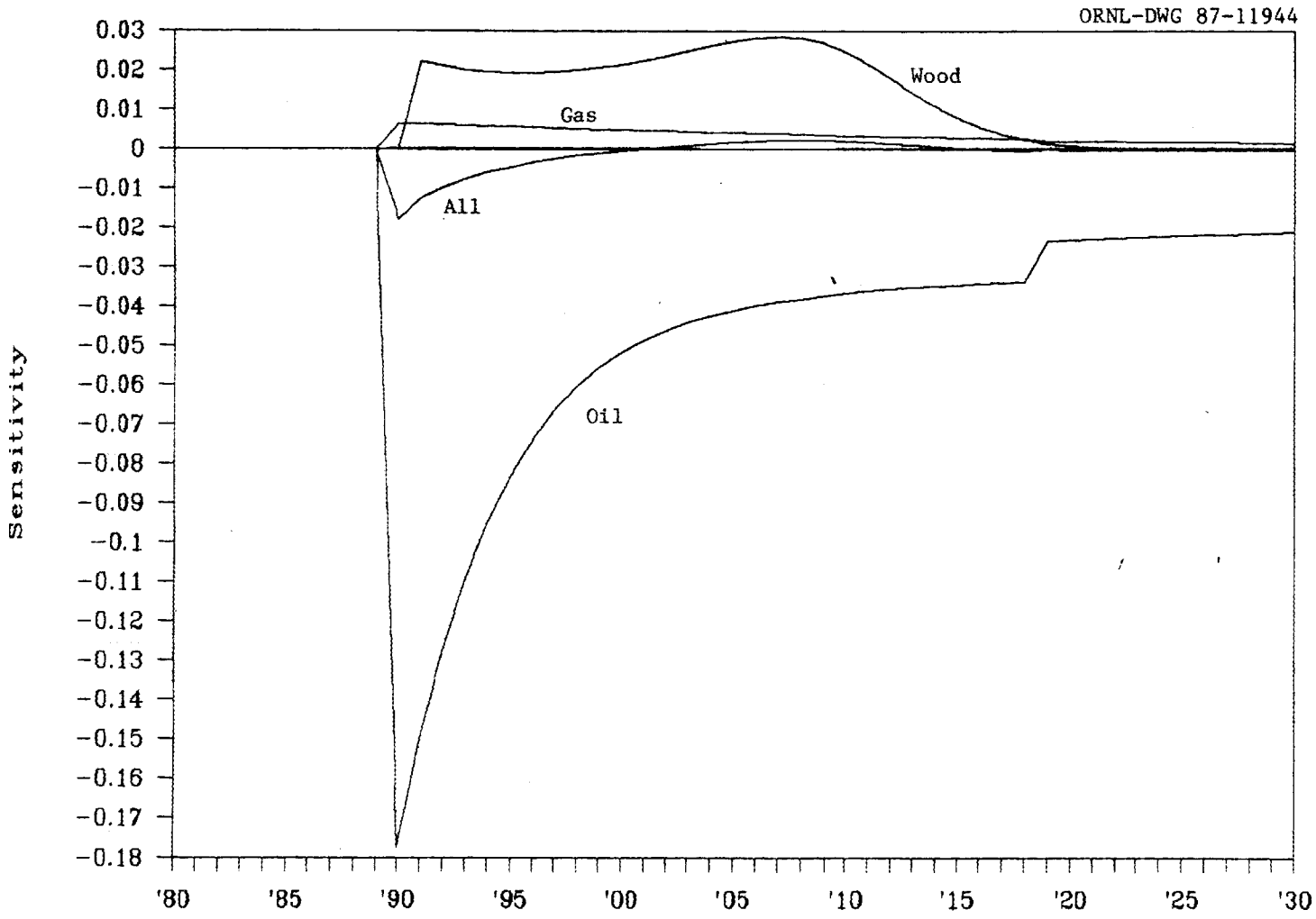

Fig. 1. Sensitivity of fuel use to 1990 price of distillate oil.

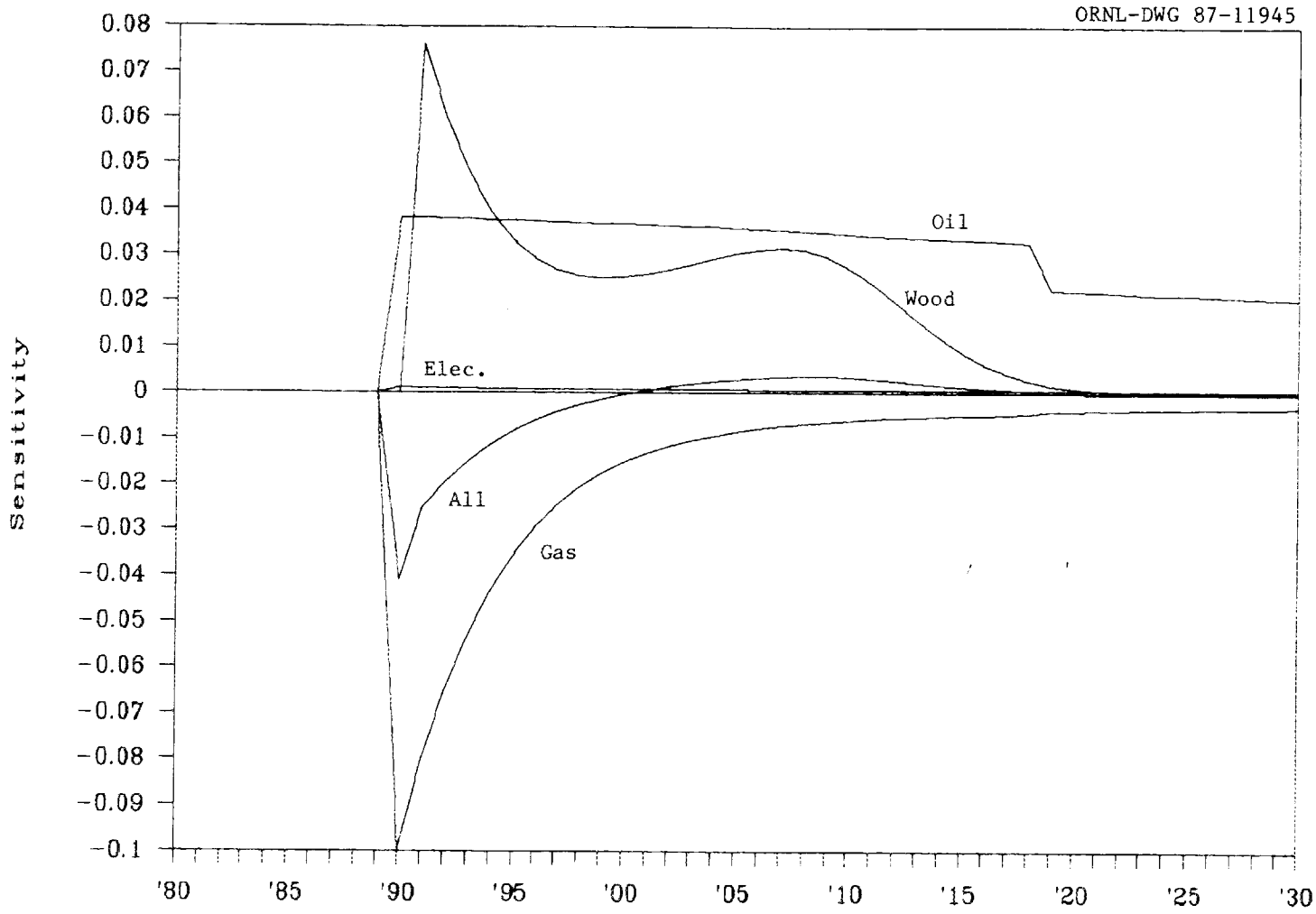

Fig. 2. Sensitivity of fuel use to 1990 price of natural gas.

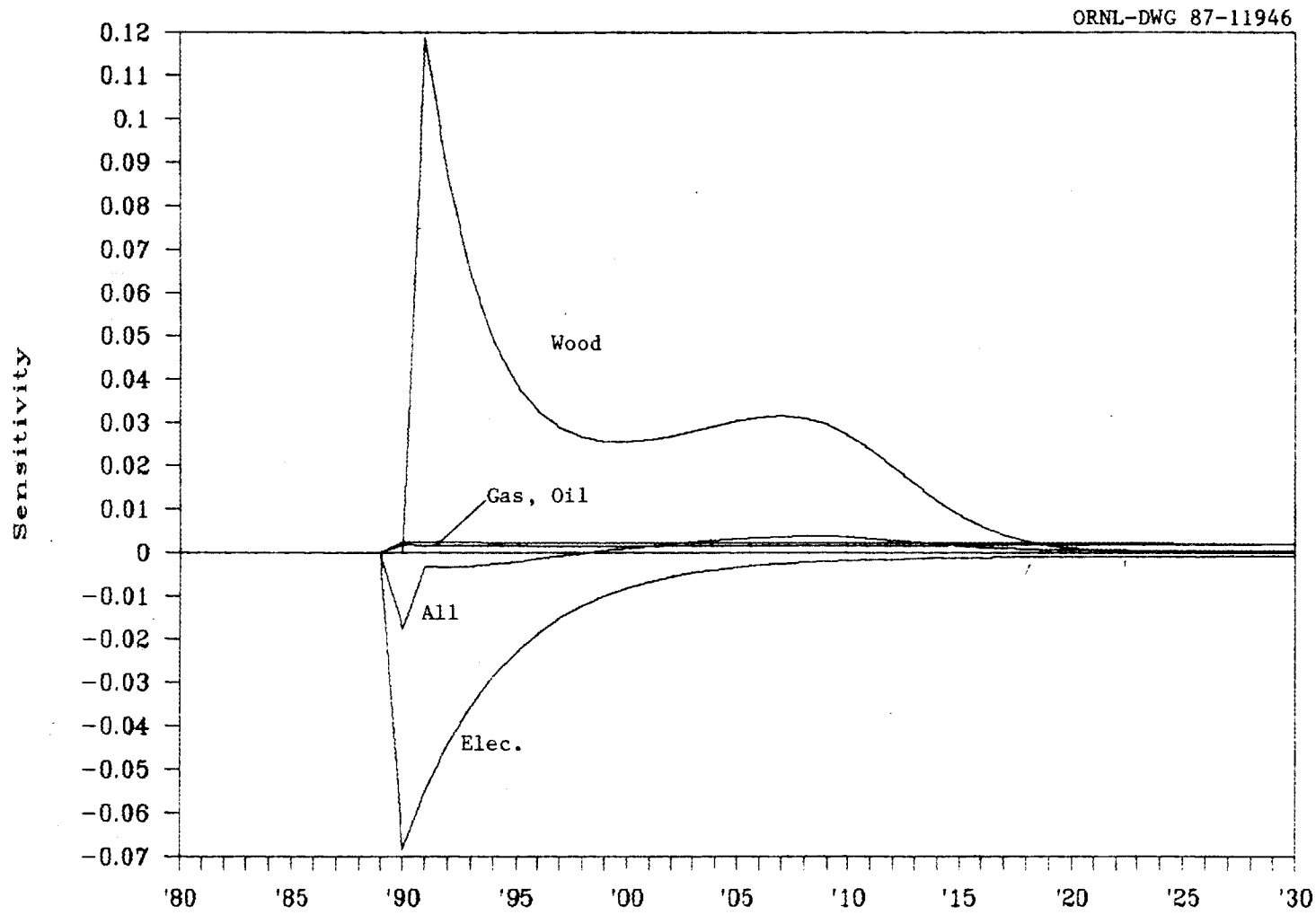

Fig. 3. Sensitivity of fuel use to 1990 price of electricity.

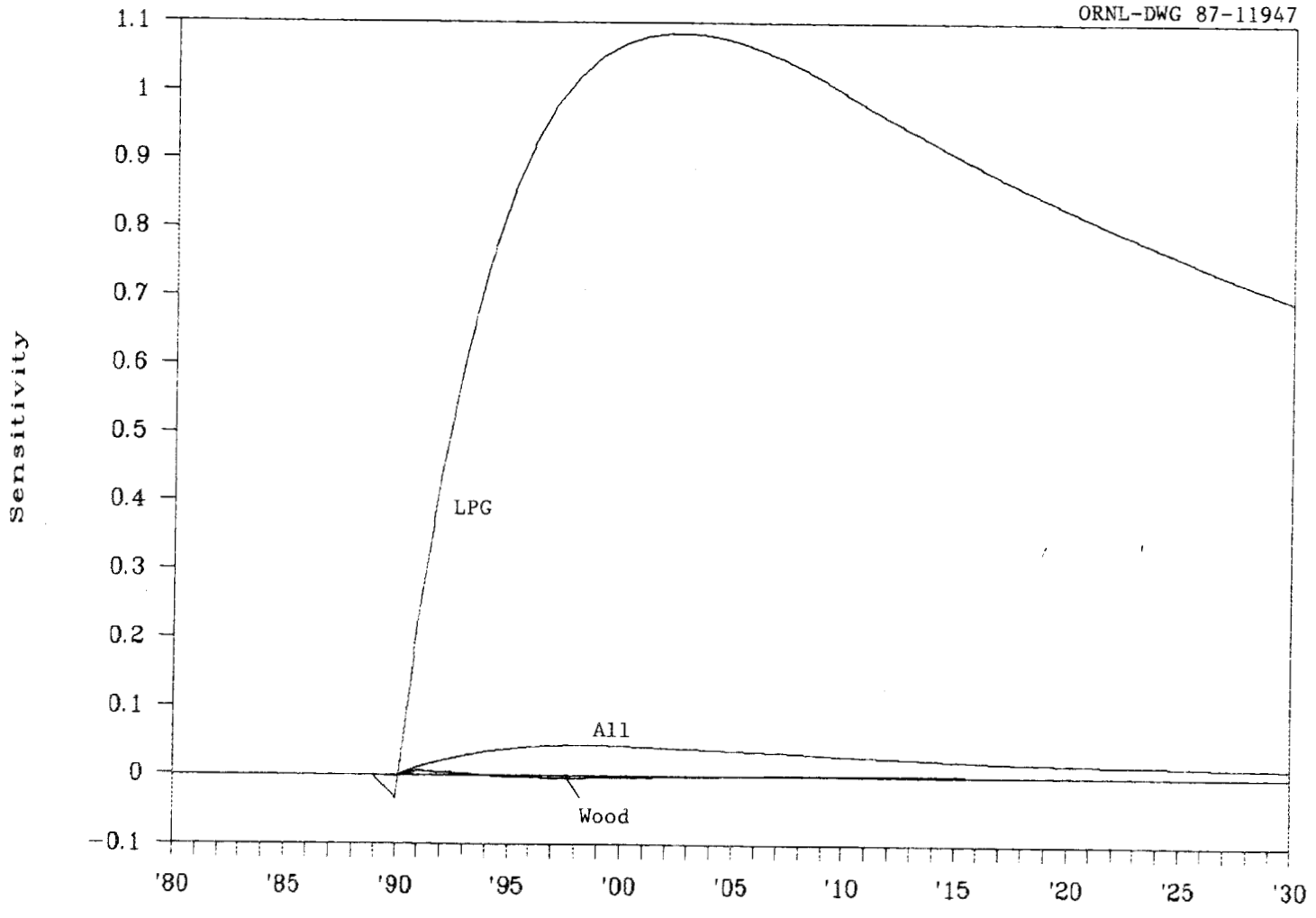

Fig. 4. Sensitivity of fuel use to 1990 price of LPG.

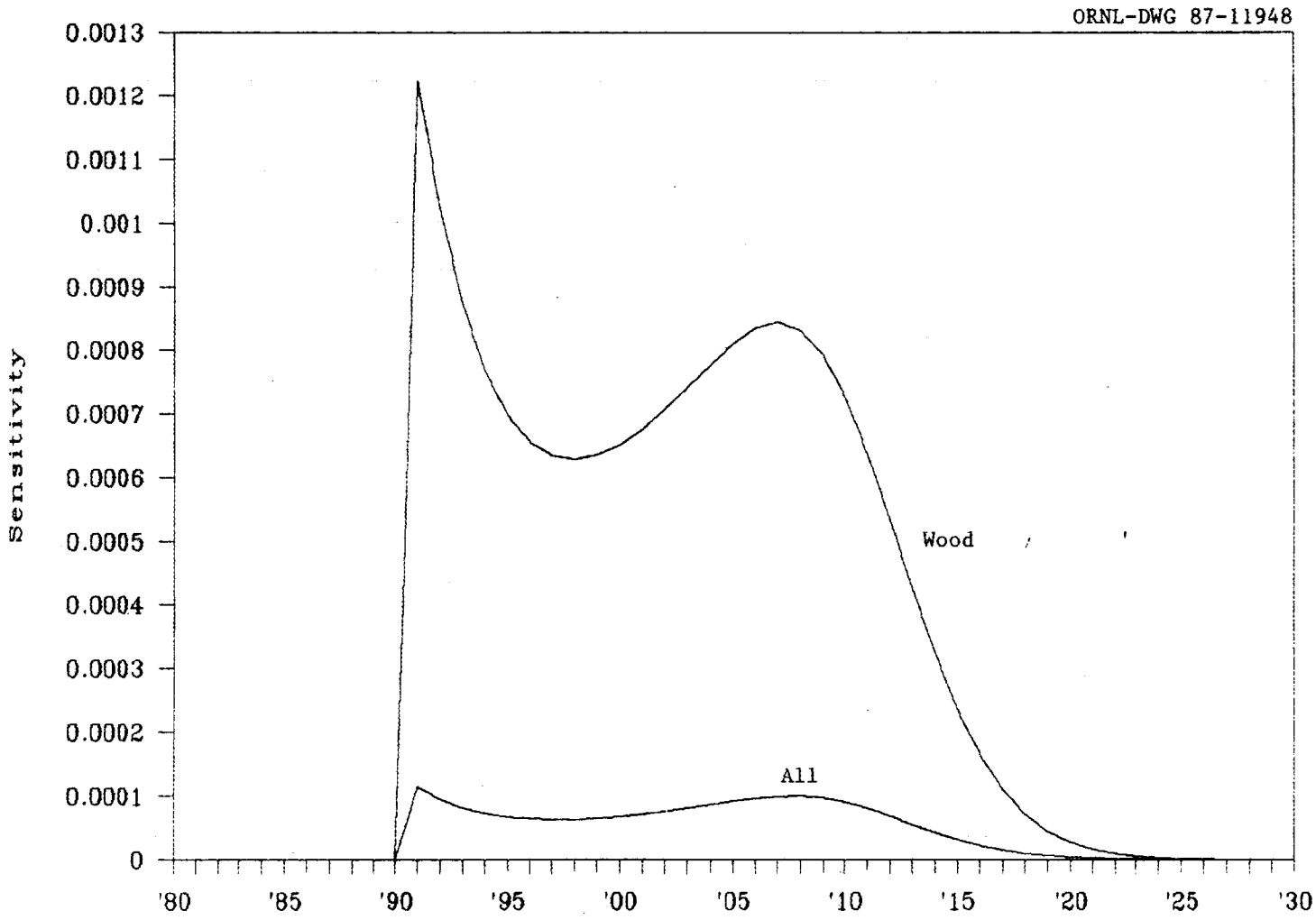

Fig. 5. Sensitivity of fuel use to 1990 price of kerosene.

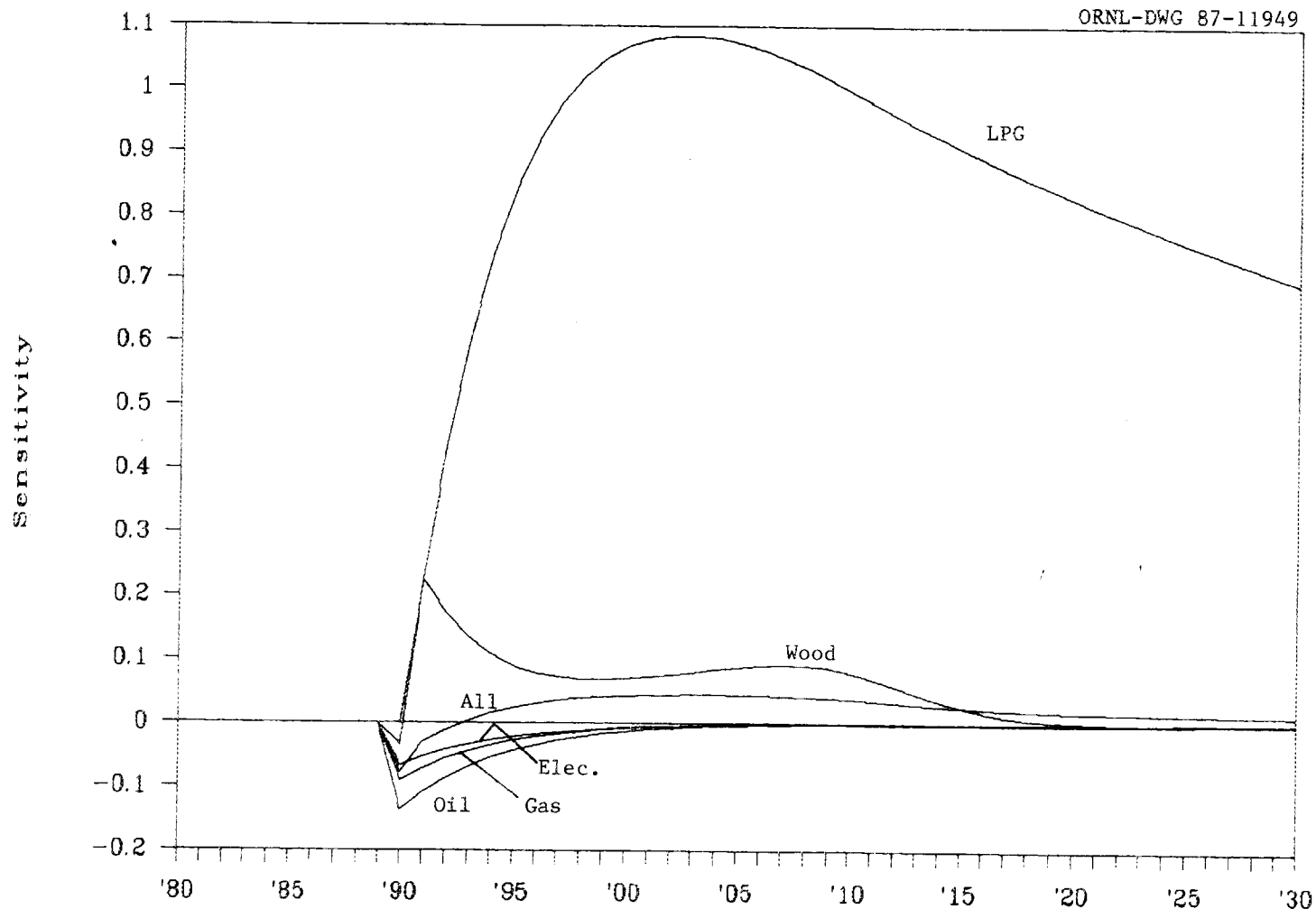

Fig. 6. Sensitivity of fuel use to 1990 price of all fuels, i.e. to a general price change.

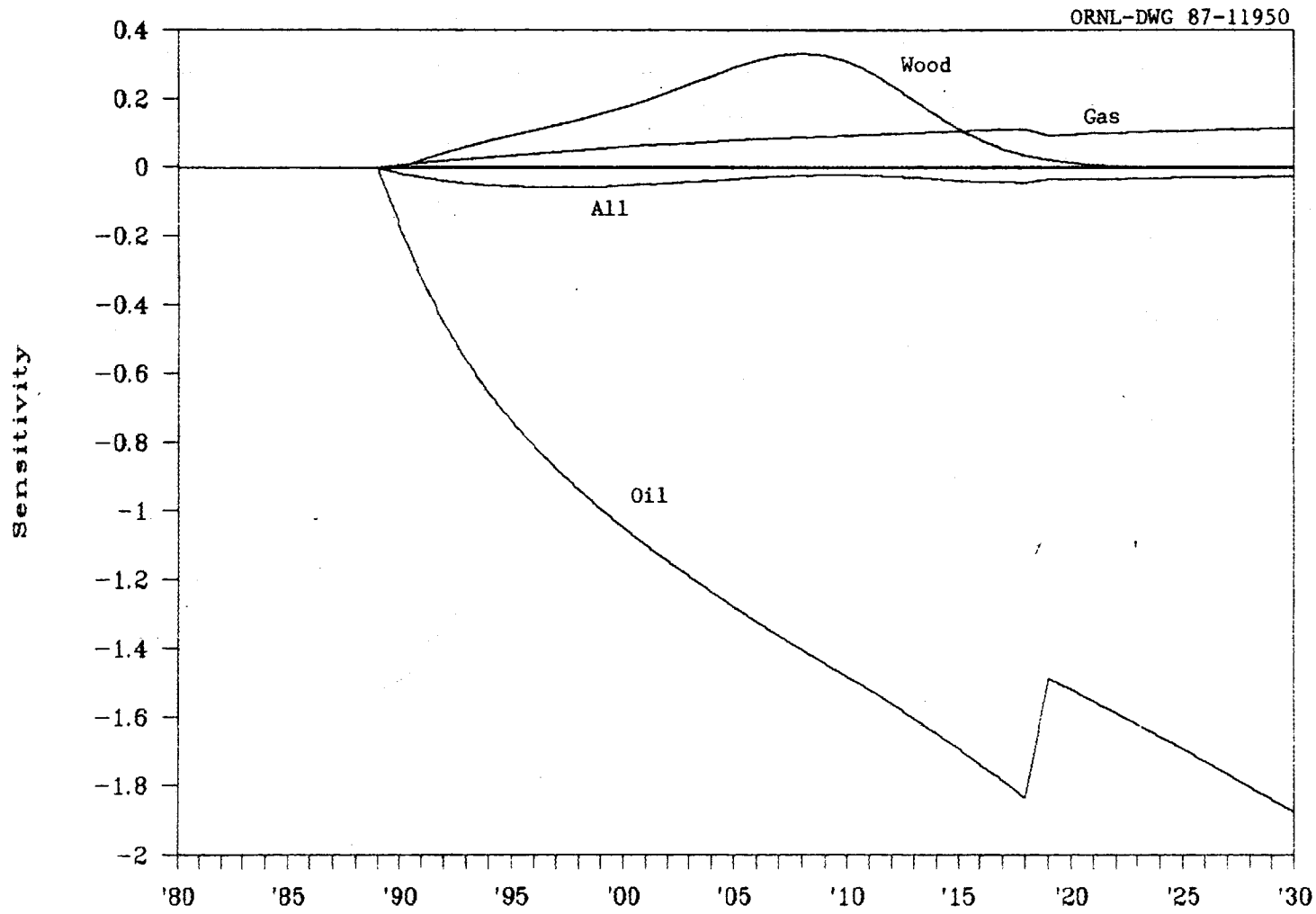

Fig. 7. Sensitivity of fuel use to post-1989 price of distillate oil.

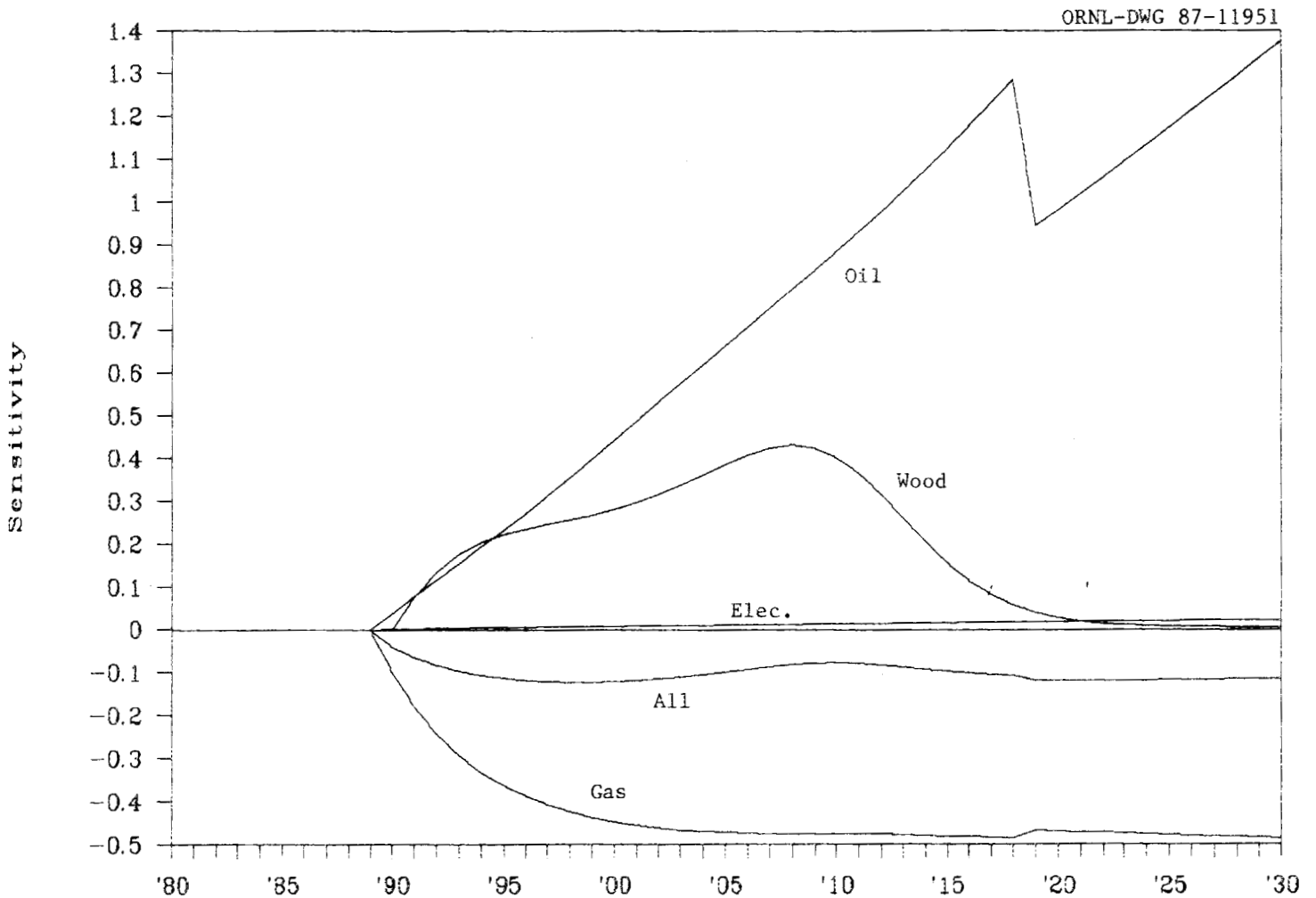

Fig. 8. Sensitivity of fuel use to post-1989 price of natural gas.

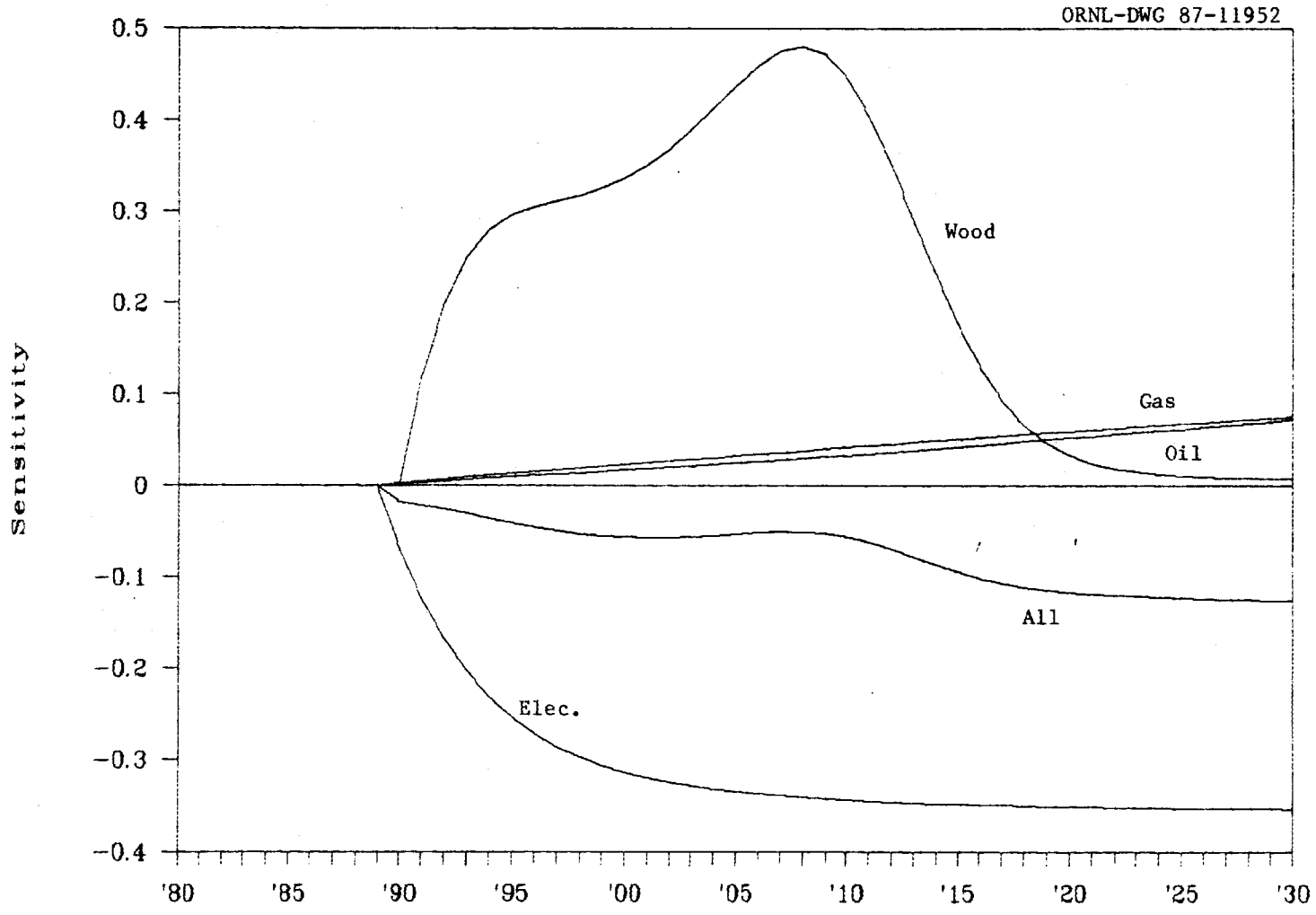

Fig. 9. Sensitivity of fuel use to post-1989 price of electricity.

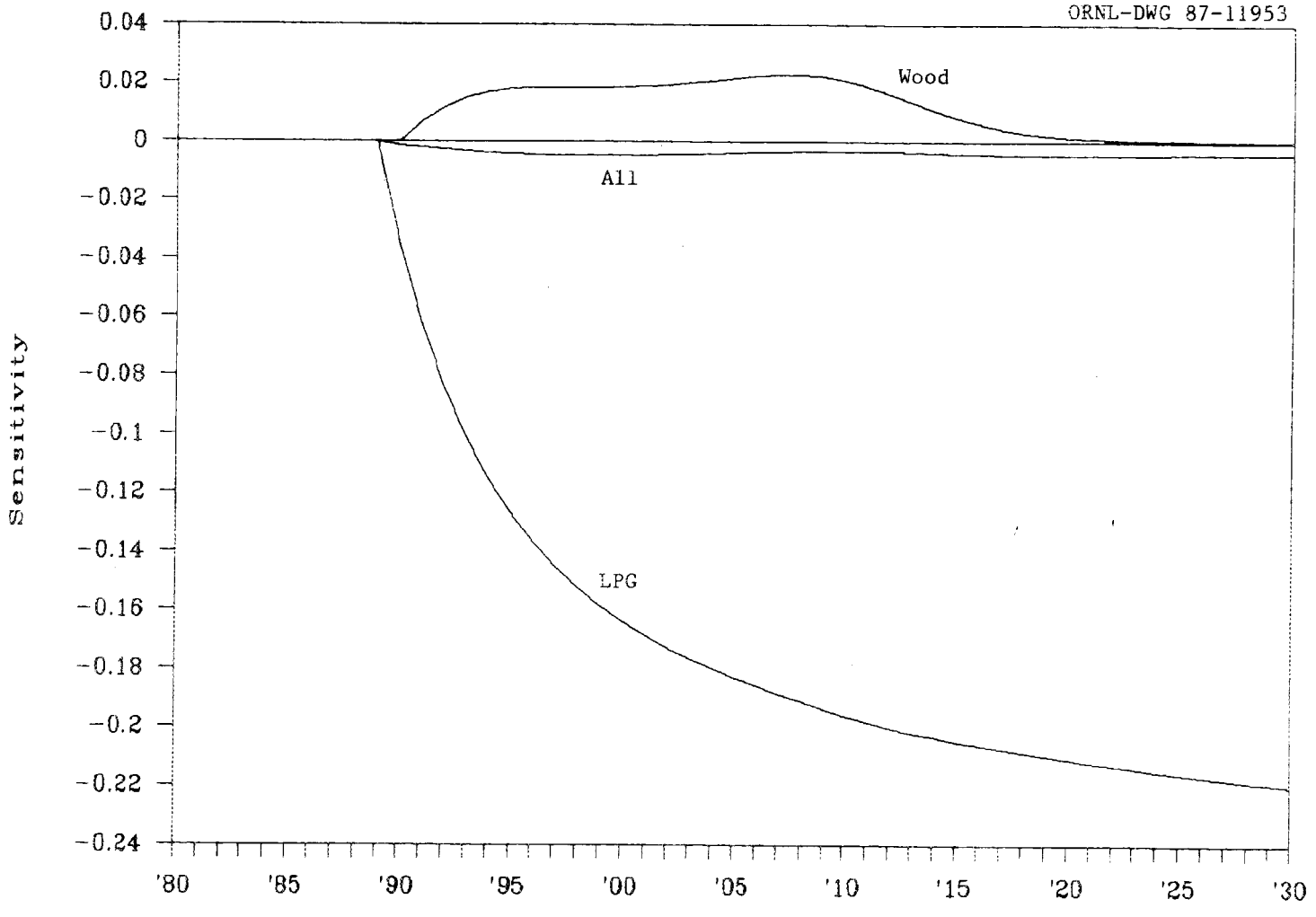

Fig. 10. Sensitivity of fuel use to post-1989 price of LPG.

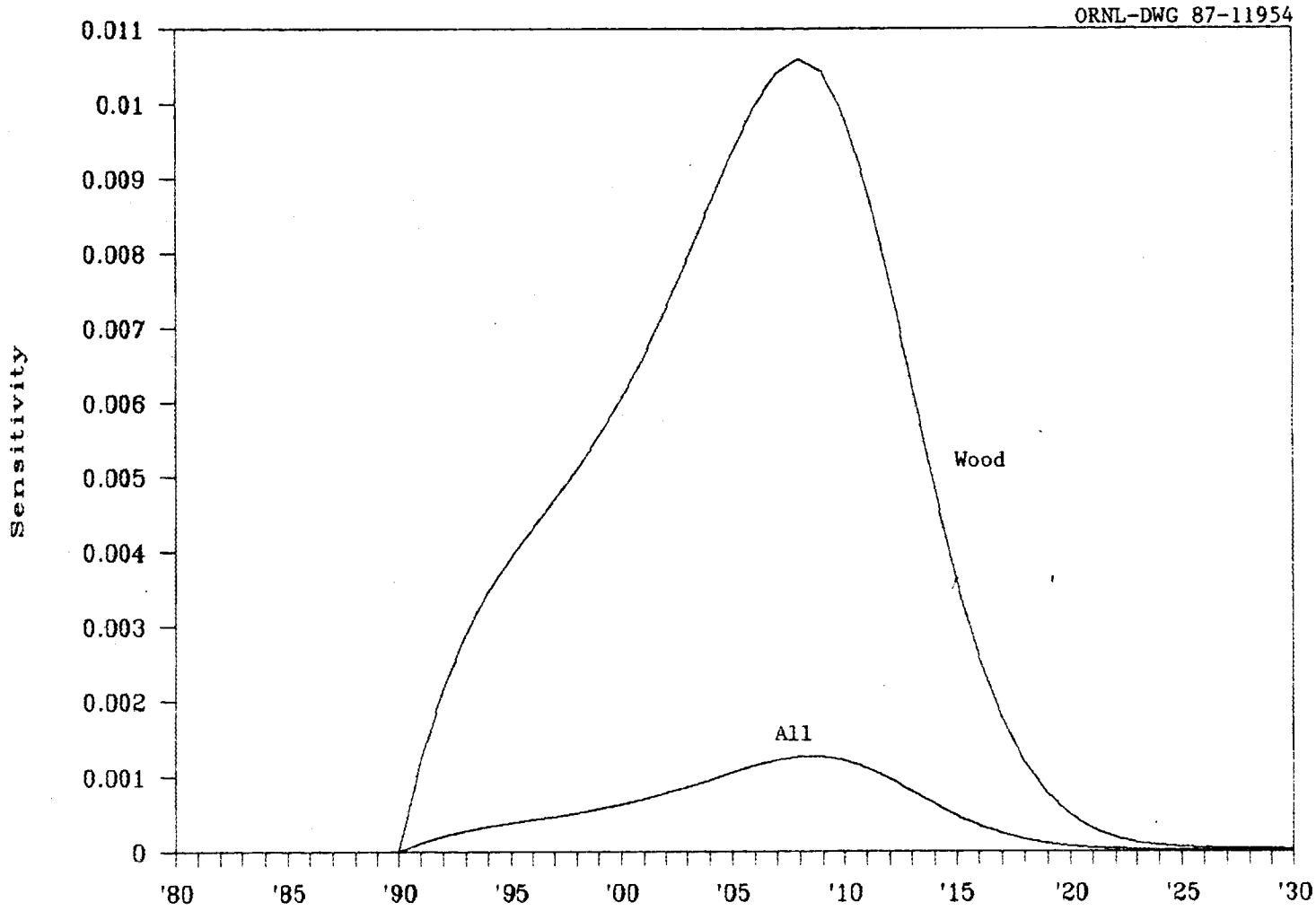

Fig. 11. Sensitivity of fuel use to post-1989 price of kerosene.

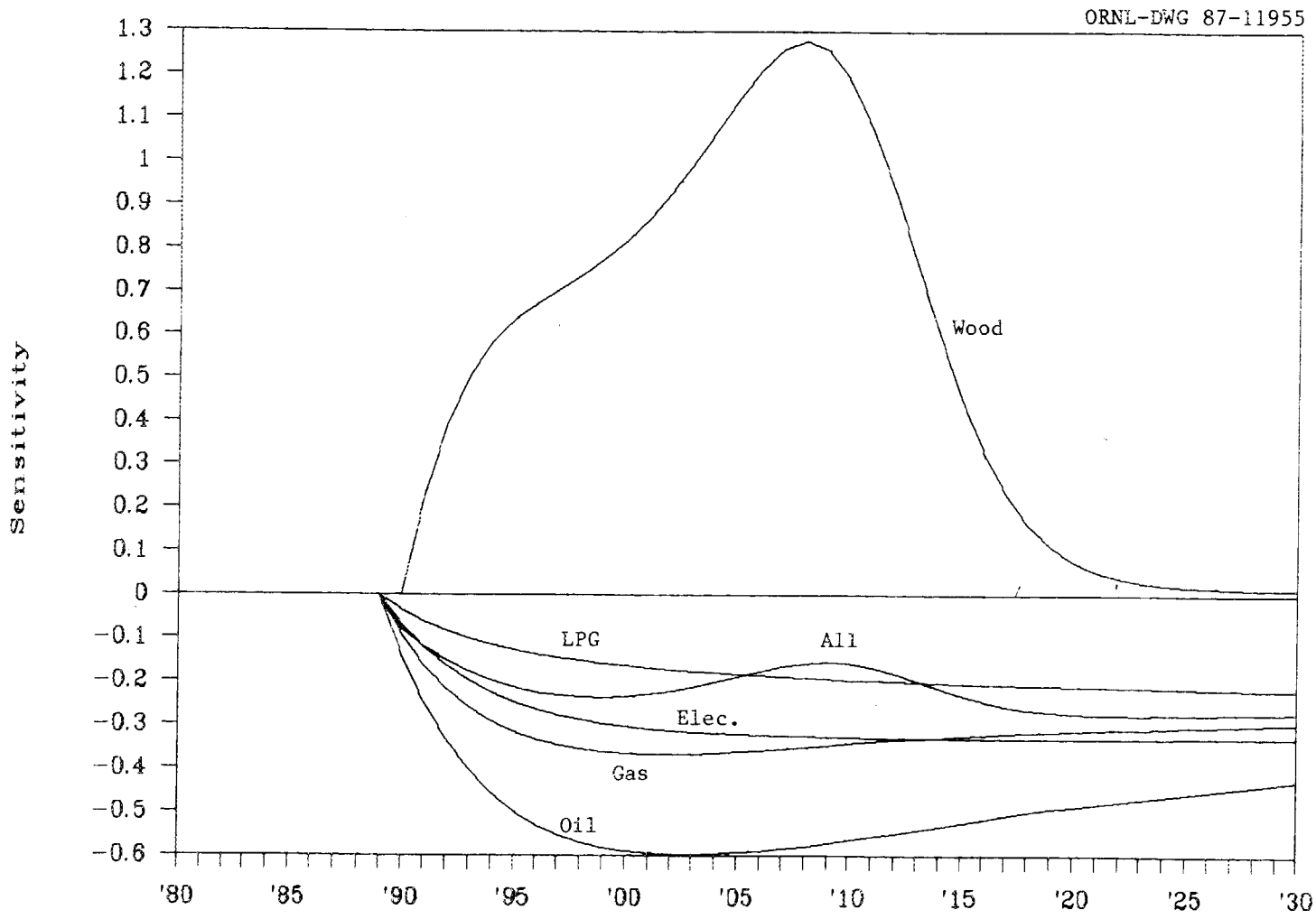

Fig. 12. Sensitivity of fuel use to post-1989 price of all fuels, i.e. to a general price change.

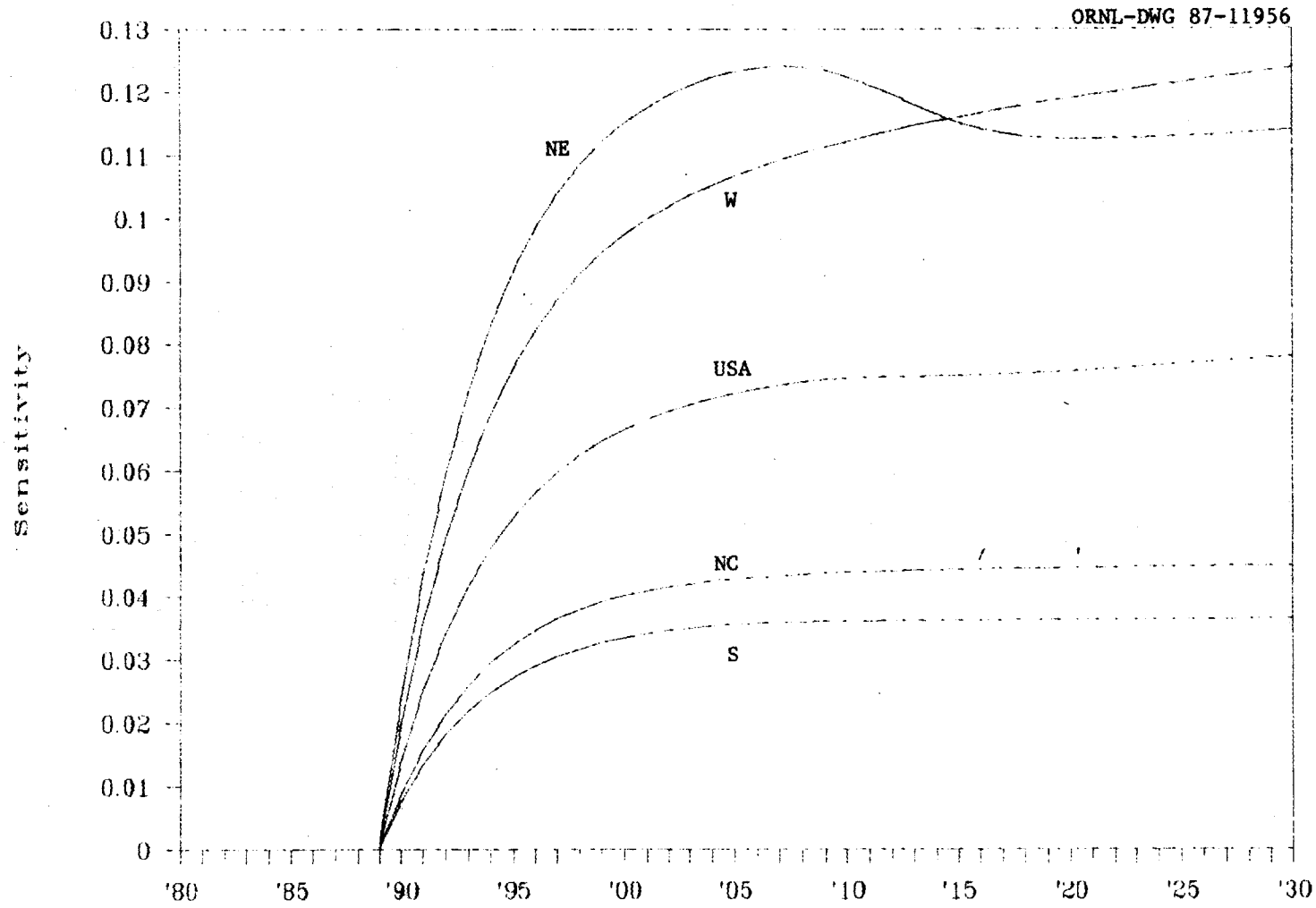

Fig. 13. Sensitivity of regional use of all fuels to post-1989 regional disposable income.

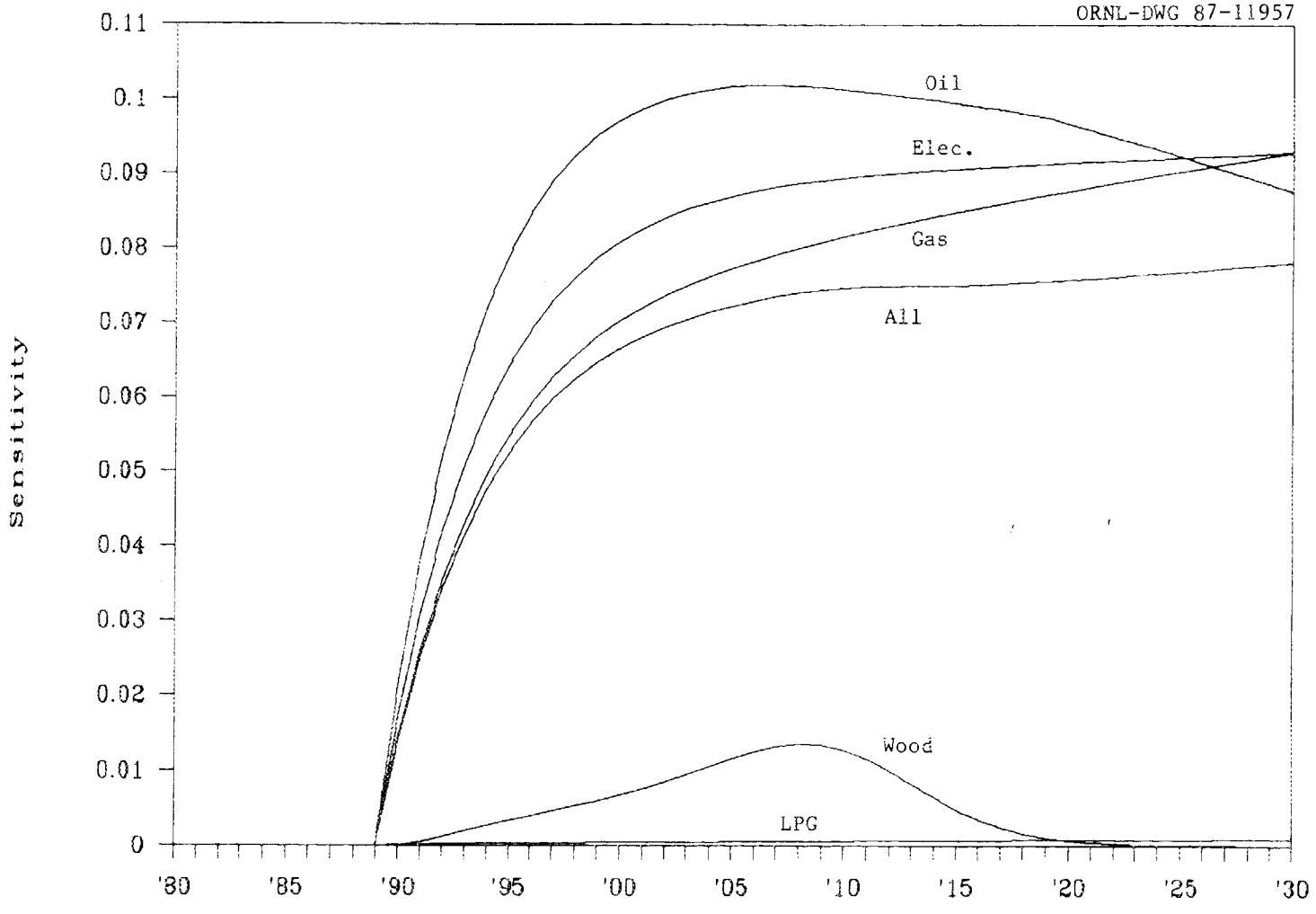

Fig. 14. Sensitivity of national fuel use to post-1989 national disposable income.

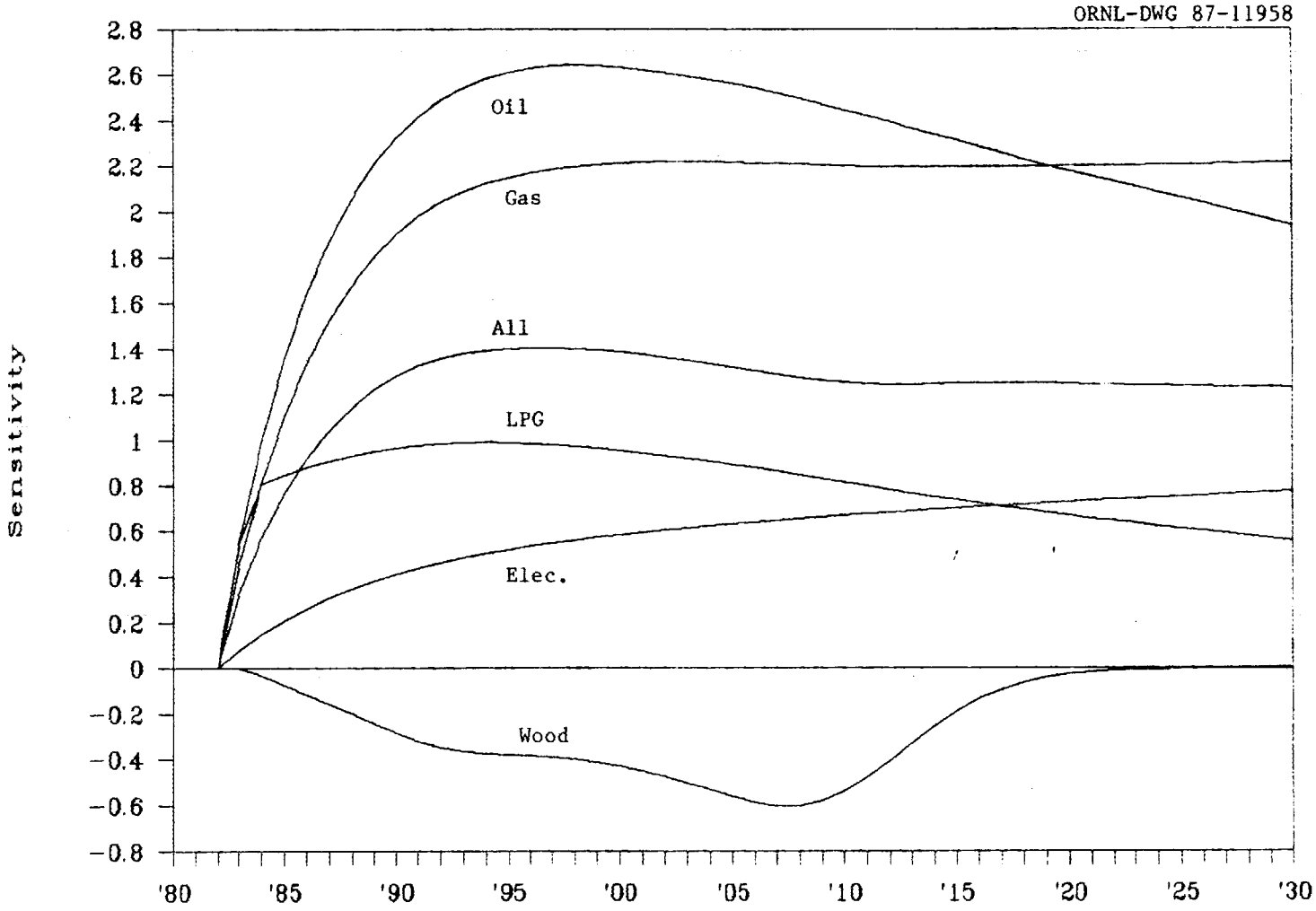

Fig. 15. Sensitivity of national residential fuel use to 1983 heating-degree-day projections, aggregated over all regions.

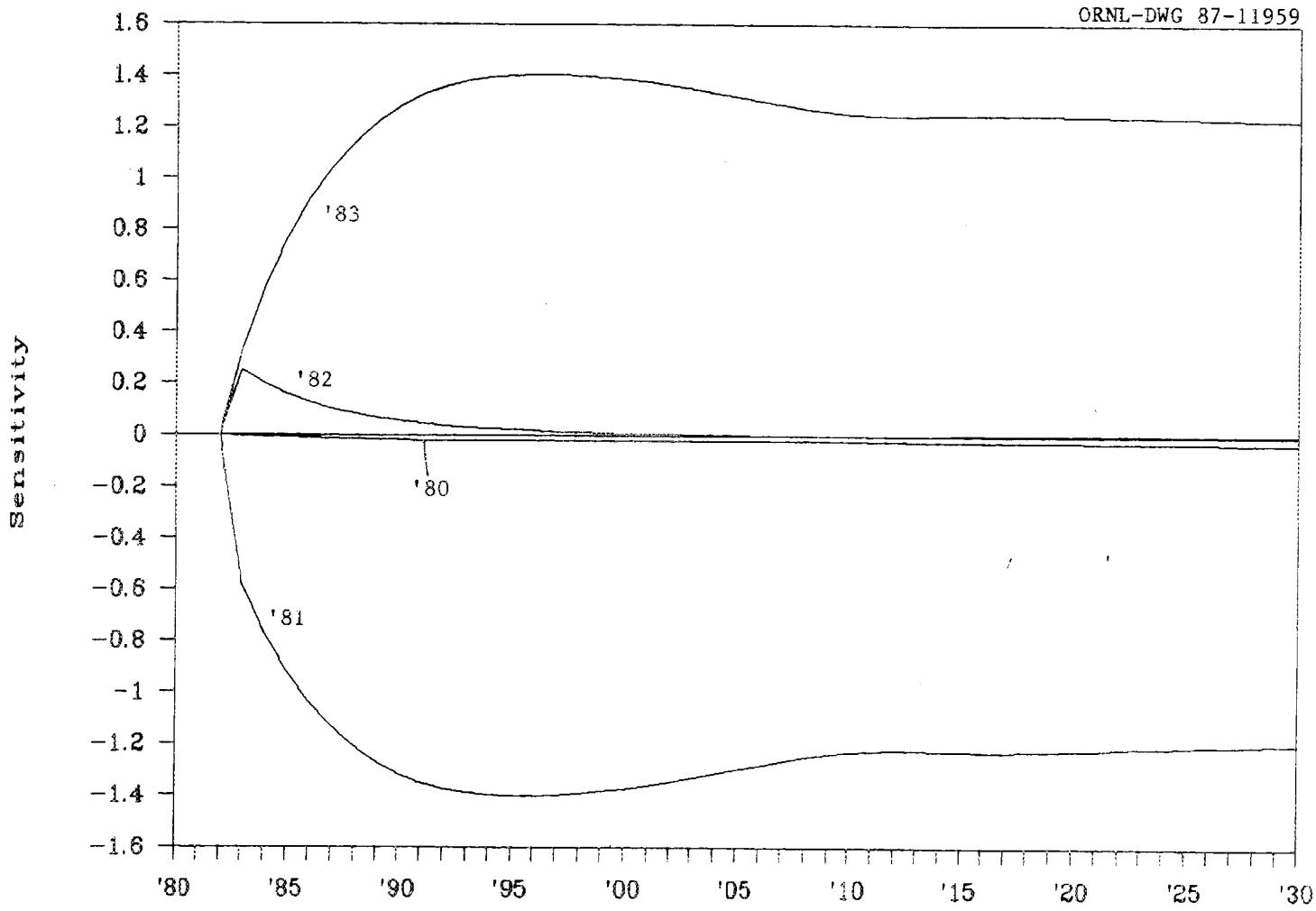

Fig. 16. Sensitivity of national residential fuel use (for all fuels) to heating-degree-day projections for the four years for which the data is used (1980 to 1983).

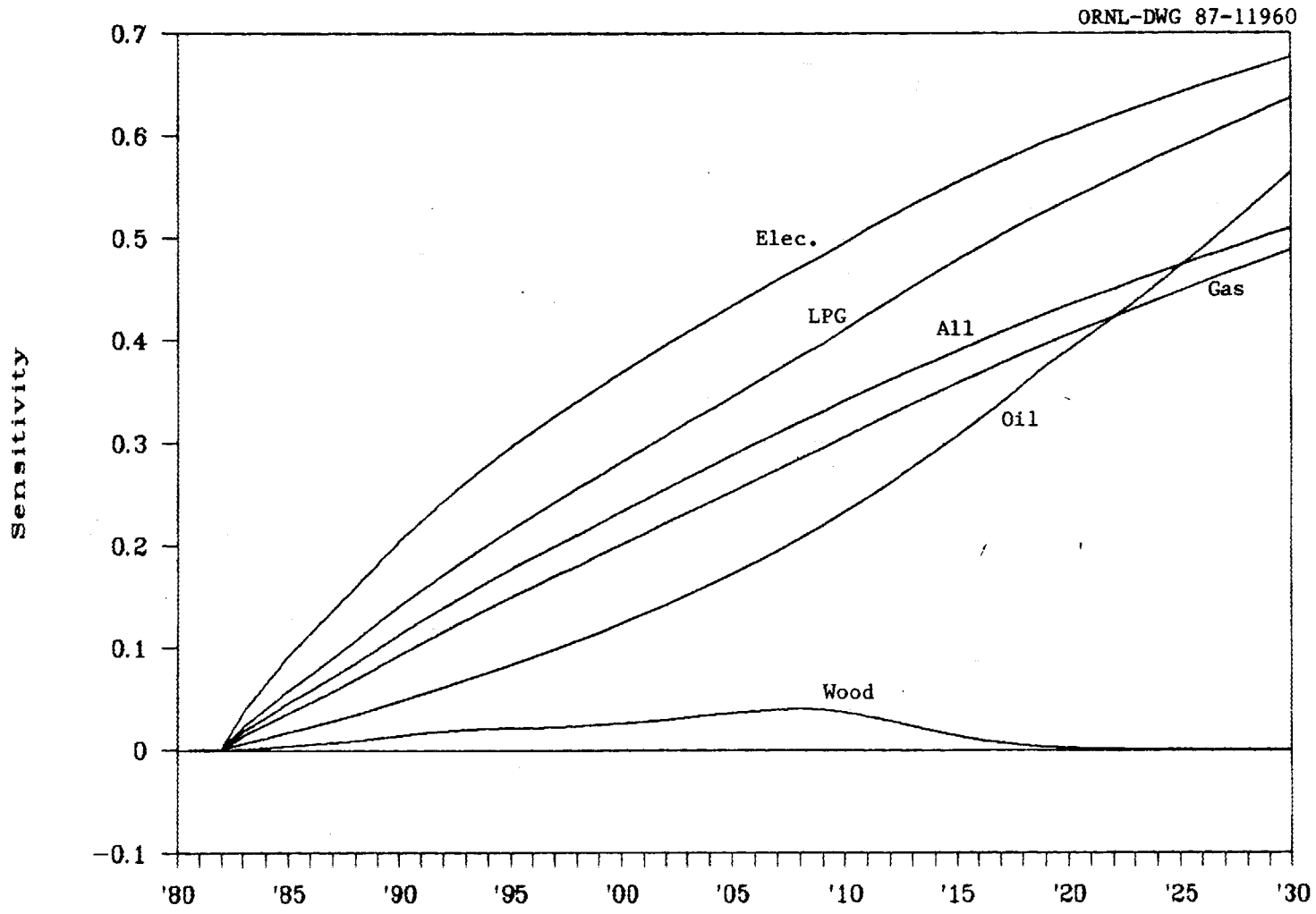

Fig. 17. Sensitivity of national residential fuel use to housing construction projections.

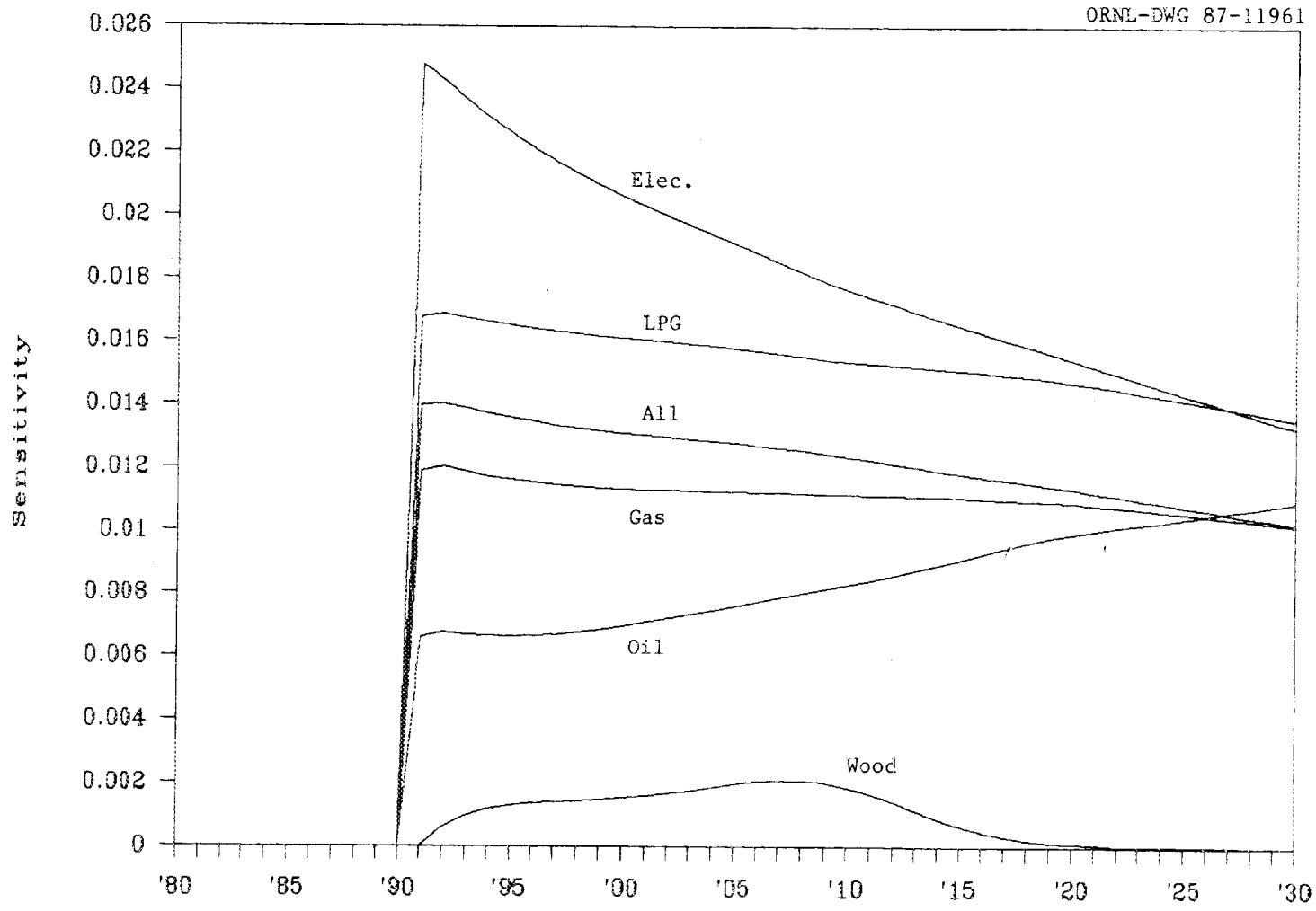

Fig. 18. Sensitivity of regional use of all fuels to 1990 housing construction rate.

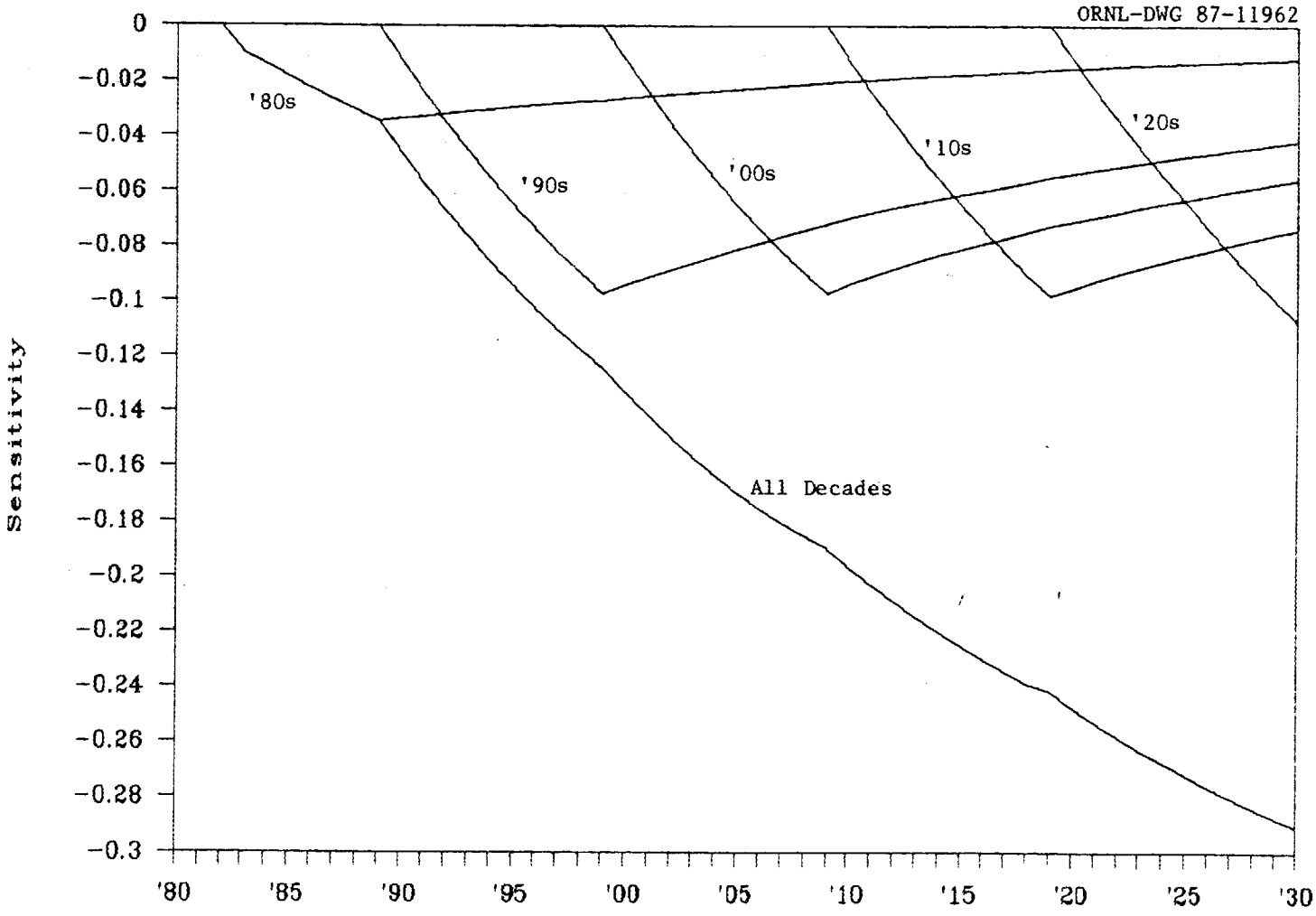

Fig. 19. Sensitivity of national fuel use to housing decay rate. Decay rate parameters are aggregated over all housing classes and vintages.

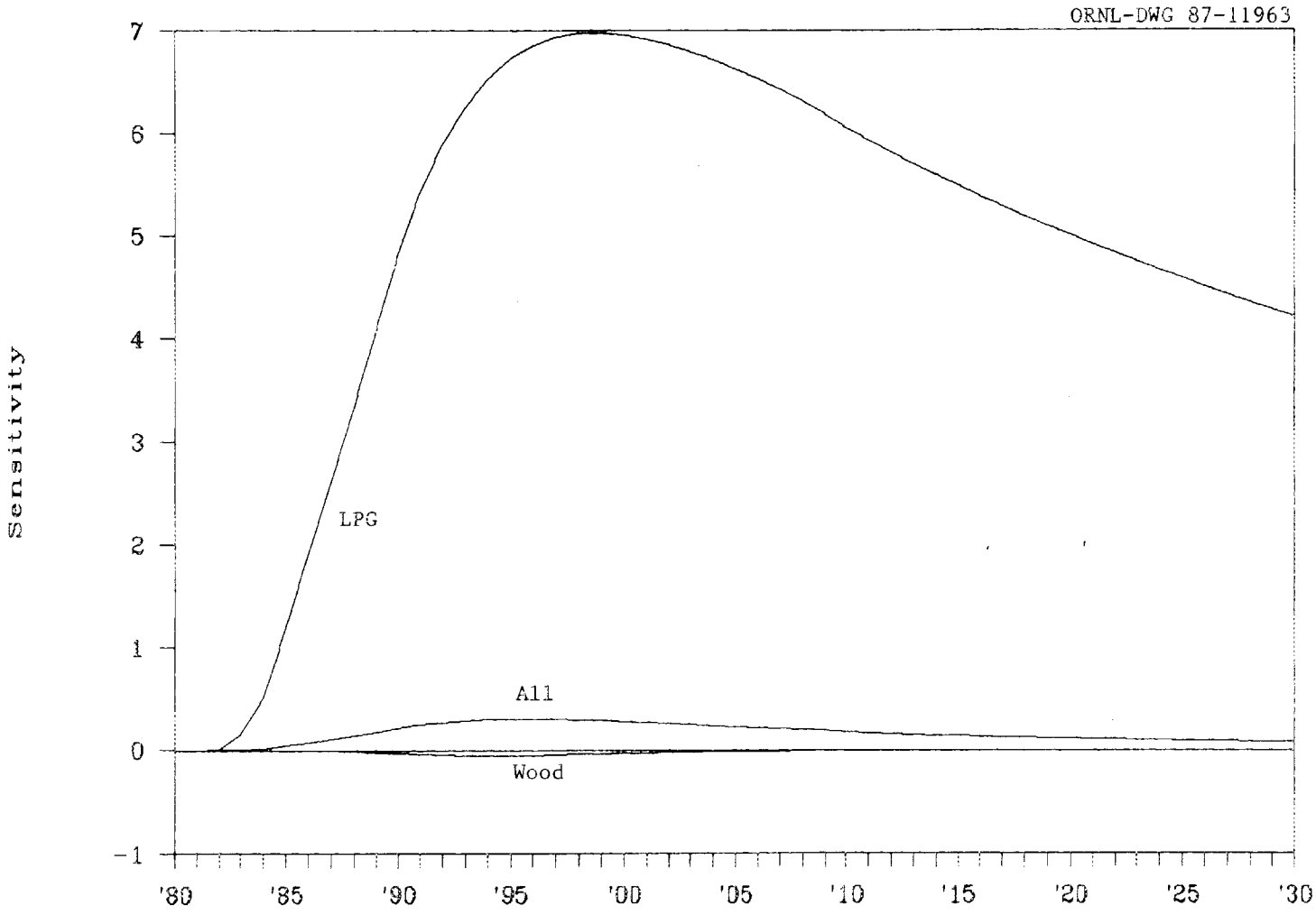

Fig. 20. Sensitivity of national fuel use to LPG space heat utilizationa growth limit.

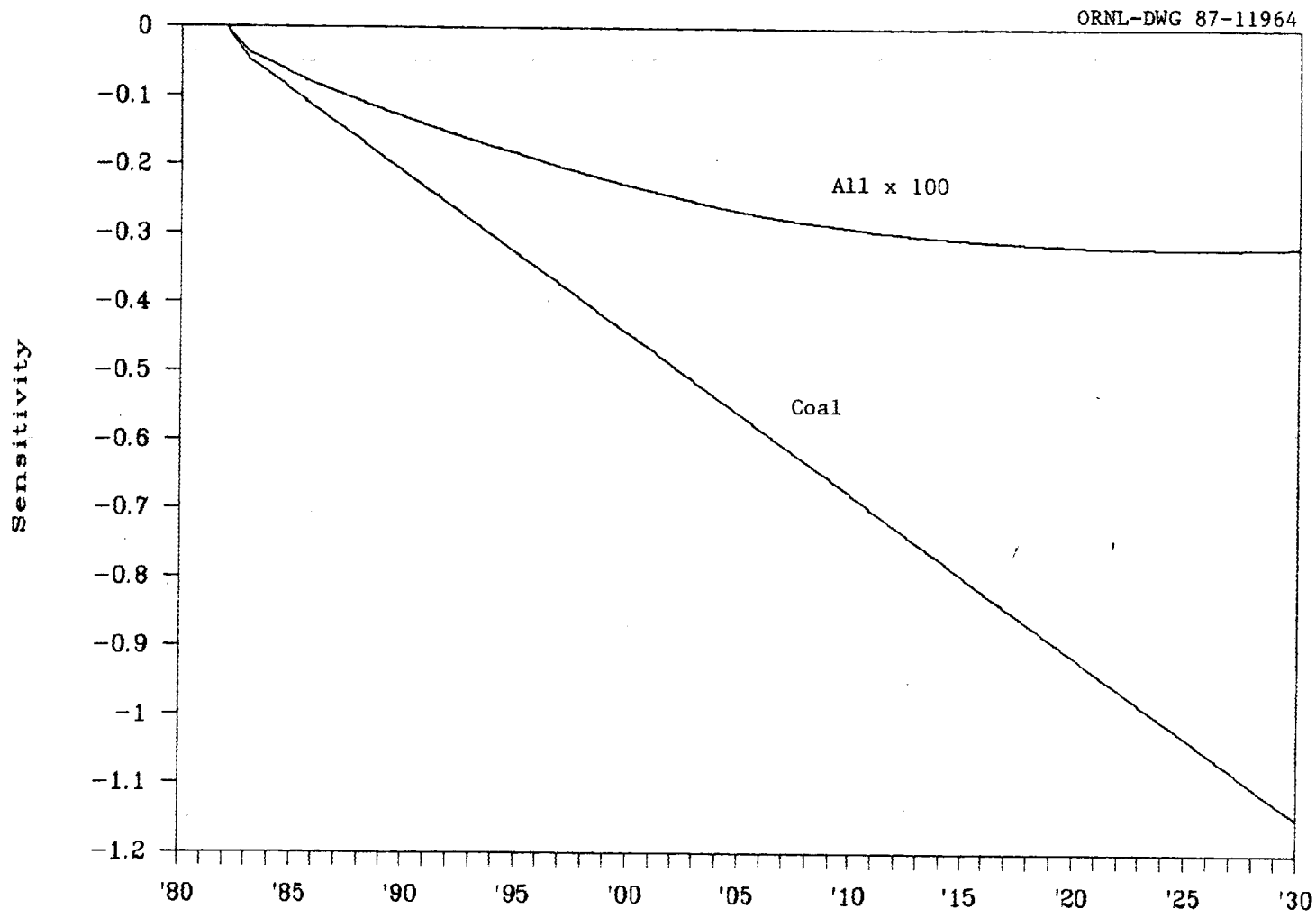

Fig. 21. Sensitivity of fuel use to coal growth parameter. Note that "All fuel" response has been magnified by a factor of 100.

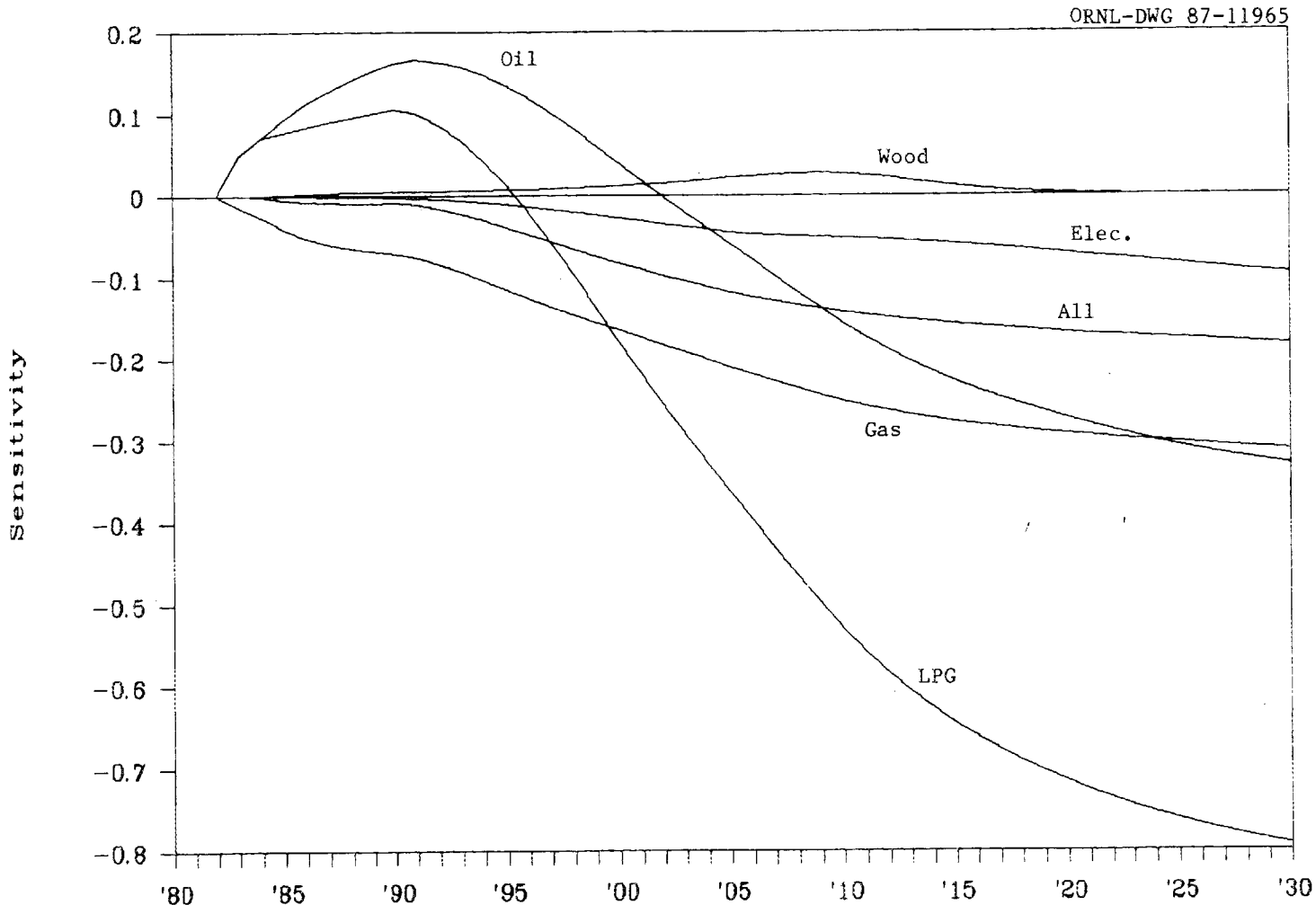

Fig. 22. Sensitivity of fuel use to price elasticities, aggregated over all end uses and regions. E.g. "oil" line displays sensitivity of oil use to a magnitude change in all price elasticities.

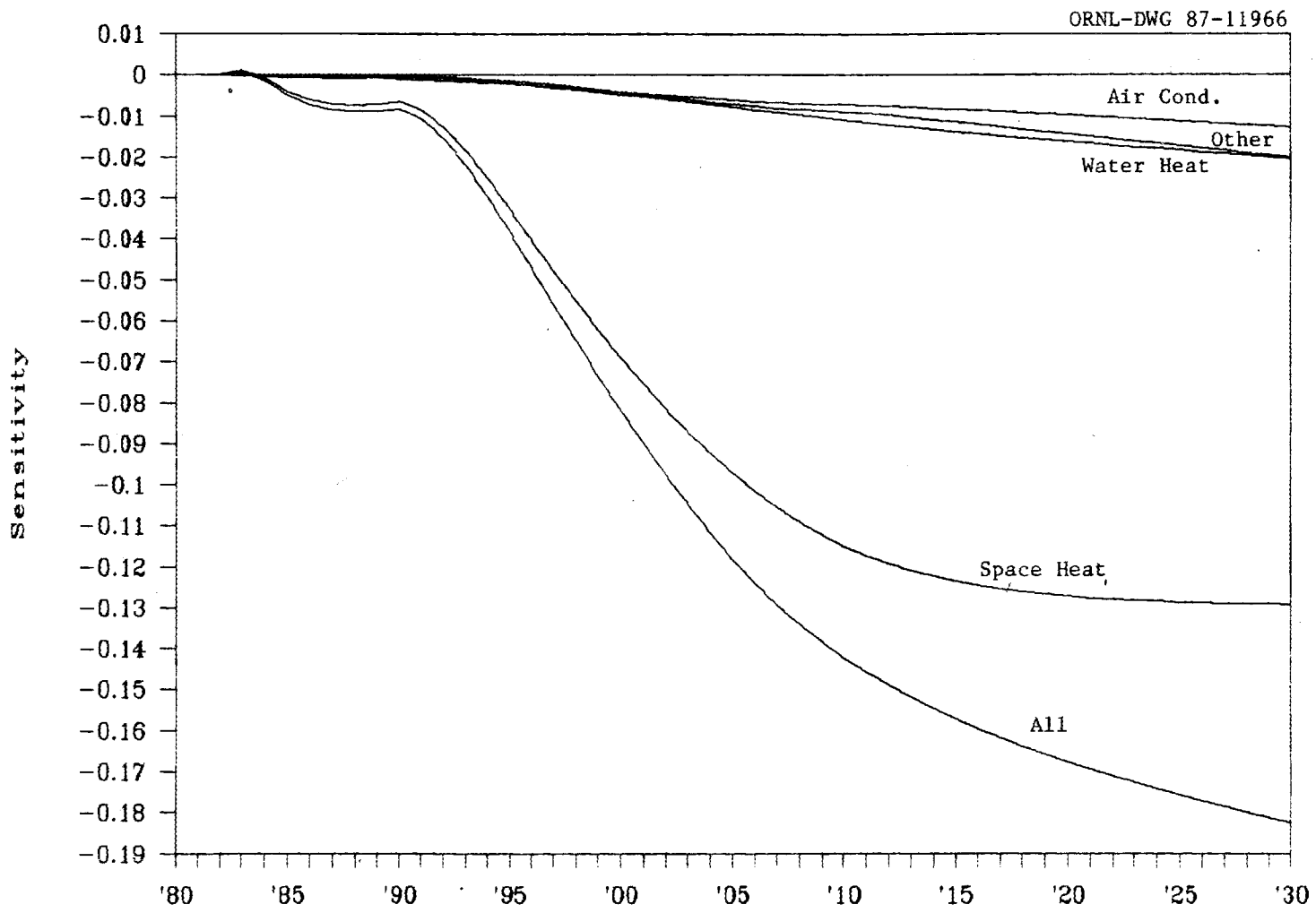

Fig. 23. Sensitivity of total fuel use to price elasticities for four end-use categories. Price elasticities are aggregated over all fuel categories and regions.

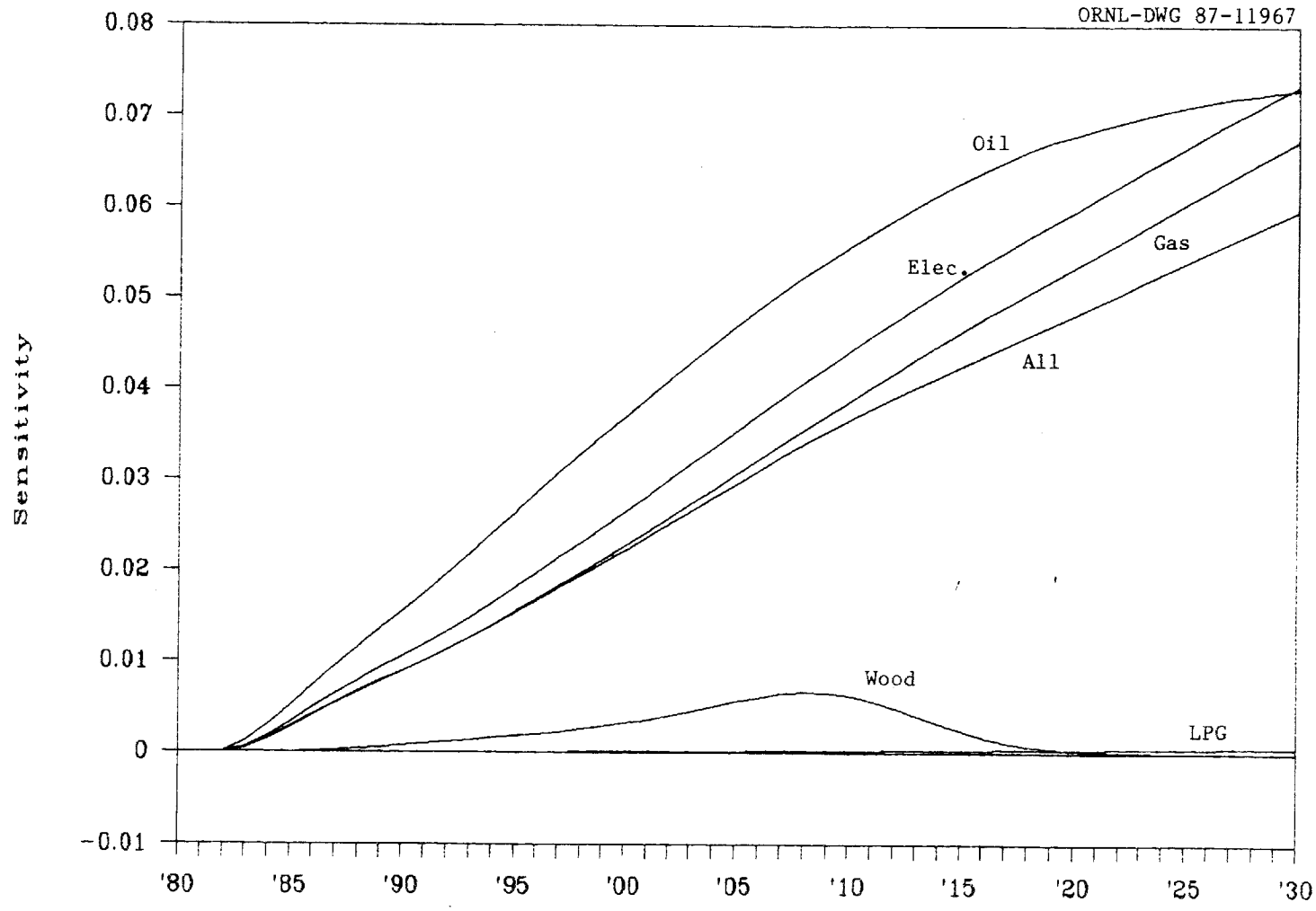

Fig. 24. Sensitivity of fuel use to income elasticities, aggregated over all end uses and regions. E.g. "oil" line displays sensitivity of oil use to a magnitude change in all income elasticities.

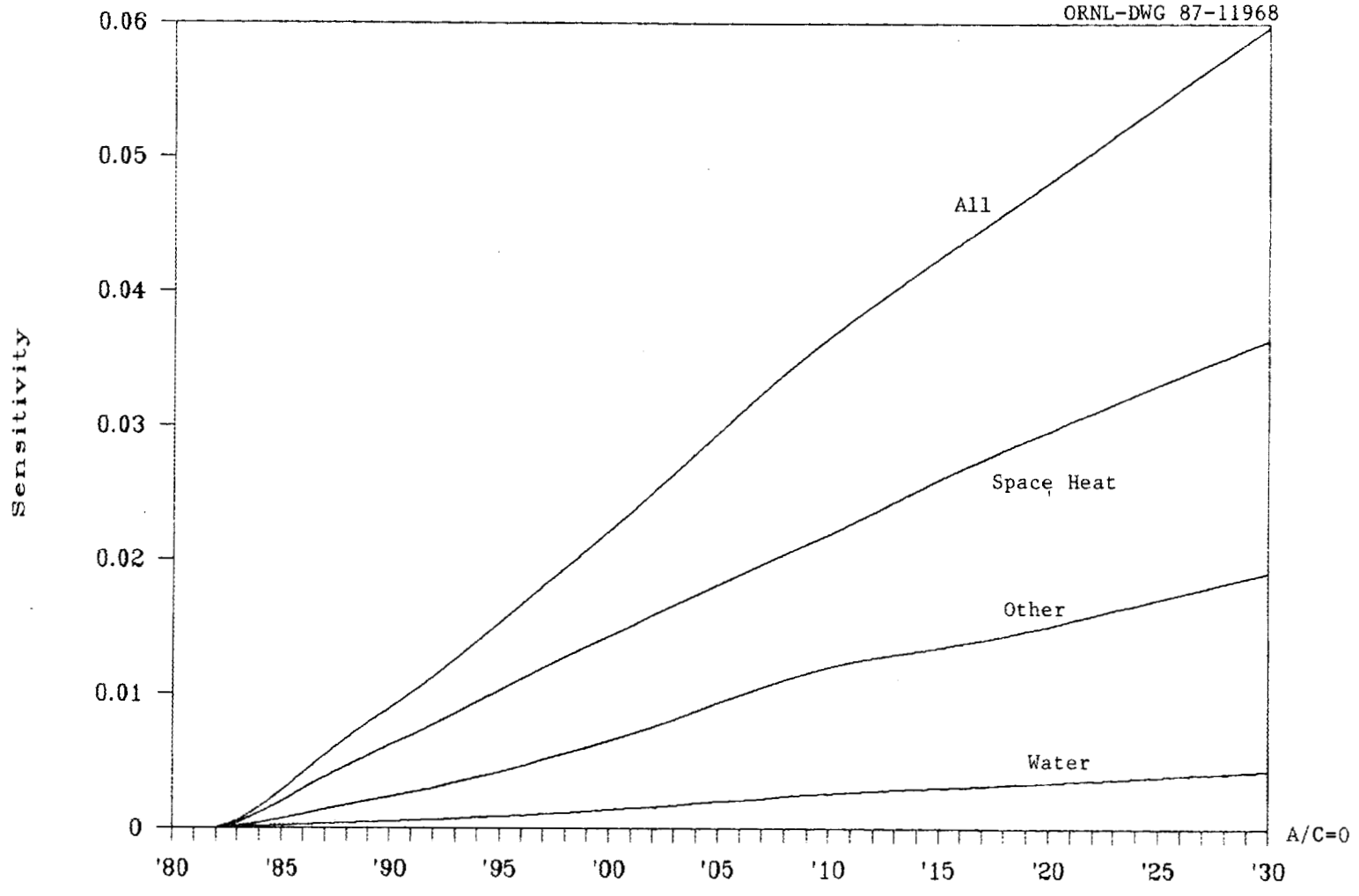

Fig. 25. Sensitivity of total fuel use to income elasticities for three end-use categories. Air conditioning elasticities' responses were calculated to be zero. Income elasticities are aggregated over all fuel categories and regions.

ACKNOWLEDGMENTS

The author would like to express his gratitude for assistance received from the following individuals during the course of this work: Ralph M. Rotty for useful suggestions on sensitivity analysis strategy for HOME2; J. E. Horwedel for instruction in GRESS operation and compatibility issues; David South for useful discussions relating to the behavior and design intent of HOME2 and for providing revisions to the code; David B. Reister and J. E. Horwedel for review of the manuscript of this report.

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