

# **Assessing the Impacts of Short-Lived Compounds on Stratospheric Ozone**



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the Cochairs of the Montreal Protocol

**Scientific Assessment Panel**

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## Executive Summary

Not all compounds containing the halogens chlorine and/or bromine are ozone-depleting substances. To be harmful to the ozone layer a substance must have a vapor pressure that is sufficient to generate a significant gas-phase concentration in the atmosphere, low solubility in water, a lifetime in the lower atmosphere that is long enough for it or its halogen-containing degradation products to reach the stratosphere, and it must be vulnerable to release of its chlorine or bromine atoms in the stratosphere.

The “steady-state” Ozone Depletion Potential (ODP) represents the relative amount of ozone destroyed by emission of a substance over its entire atmospheric lifetime. Complex numerical models are used to evaluate the ODP. The “steady-state” ODP is most useful for substances with atmospheric lifetimes comparable to or longer than CFC-11 (50 years). For substances with a relative short atmospheric lifetime (e.g., 5 years), the “time-dependent” ODP gives a more meaningful picture of the near-term effects of the substance. The “time-dependent” ODP provides a measure of relative ozone loss over specific time horizons, e.g. 5 years. Such ODPs have been provided in the Scientific Assessment Reports for a suite of compounds.

However, short-lived compounds (e.g., weeks to months) present special problems. The accurate determination of an ODP depends on quantifying the amount of halogen delivered to the stratosphere and determining how the chlorine- or bromine-containing species affect the ozone in the stratosphere. Because transport to the stratosphere mainly occurs through the tropical tropopause, a short-lived species might undergo significant loss through various removal processes in the troposphere before reaching the tropics. The amount reaching the stratosphere is thus strongly dependent on the latitude/longitude and season of emission. Furthermore, the reactions and reaction products produced throughout the atmosphere must be taken into account because it is possible that the reaction products are active in affecting the ozone layer. Unfortunately, the reaction pathways and degradation products of the short-lived compounds are frequently unknown. Because the time scales of transport and interactions among the reaction products are so short for such compounds, existing steady-state and two-dimensional methods of determining ODPs are inadequate. Three-dimensional models that simulate tropospheric meteorology must be used.

New research since the 1998 report confirmed that the ODP of short-lived compounds varies according to the latitude, longitude, and time of emission (as much as with a factor of 10). Three dimensional models were used to calculate the ODP of n-propyl bromide emitted from different geographic regions. Three recent studies show that in the case of n-propyl bromide, the ODP for emissions in the tropics can be up to a factor of 30 or more greater than the ODP for emissions at northern latitudes in summer. From these and other research results, it is clear that it is not possible to describe a single ODP value for the very short-lived compounds.

The scientific community provides examples of two approaches that the Parties might consider in assessing the effects of short-lived substances on the ozone layer: (i) the estimation of geographically-dependent ODPs, or (ii) an evaluation of the contribution of the compound to the stratospheric halogen loading from the present to 2050, using a projected emission scenario that accounts for the estimated volume and location of emissions, as a means of comparing the relative damage of the different substances. It is stressed that significant uncertainties remain in the complicated process of evaluating halogen loadings

and ODPs of short-lived substances. The evaluation of the ozone impact of a newly proposed short-lived substance is a more complex and expensive research endeavor than past evaluations of long-lived substances.

## Introduction

This report responds to Decision X/8 (paragraph 5-part a) of the 10<sup>th</sup> Meeting of the Parties to the Montreal Protocol on Substances that Deplete the Ozone Layer, which states:

*Decision X-8. New substances with ozone-depleting potential*

*5. To request the Technology and Economic Assessment Panel and the Science Assessment Panel, taking into account, as appropriate, assessments carried out under decision IX/24, to collaborate in undertaking further assessments:*

*(a) to determine whether substances such as n-propyl bromide, with a very short atmosphere lifetime of less than one month, pose a threat to the ozone layer*

This report contains four major sections:

- › a brief review of the underlying scientific concepts related to ODPs
- › a description of the difficulties of assessing ODPs for short-lived compounds
- › an update on the latest scientific research on the topic of ODPs for short-lived compounds
- › a discussion of policy-relevant scientific issues that are not yet resolved

## I. Underlying Scientific Concepts

### Characteristics of an Ozone-Depleting Substance (ODS) – The Classical View of Long-Lived Substances

The halocarbons are a family of substances that contain carbon plus any of the four halogens: fluorine, chlorine, bromine, and/or iodine. Chlorine and bromine are the primary atmospheric halogens that are reactive toward stratospheric ozone. Not all compounds containing chlorine and/or bromine are significant ozone-depleting substances (ODSs). A few fundamental physical/chemical characteristics are common to those substances that are harmful to the ozone layer:

- *At atmospheric temperatures at the point of emission, the substance must have a vapor pressure that is sufficient to generate a significant gas-phase concentration in the atmosphere.* From a practical standpoint, this means that substances that are solids at room temperature can be eliminated from consideration as potentially harmful to the ozone layer.
- *The substance must have a lifetime in the lower atmosphere that is long enough for the substance to reach the stratosphere.* Entry into the stratosphere occurs primarily via the tropical tropopause (i.e., the boundary between the troposphere and the stratosphere). Trace gases enter the stratosphere with the upward bulk flow of air at the tropical tropopause, rise in the stratosphere at tropical latitudes, and then spread poleward to the mid- and high-latitude stratosphere. Depending on latitude/longitude and season of emission, substances might have a journey of several months in the troposphere before they reach the tropics and then enter the stratosphere. Both physical and chemical processes can act to remove substances from the lower atmosphere, thereby diminishing the amount that can enter the stratosphere. Substances that are soluble in water can dissolve in atmospheric water droplets, and then can be removed by precipitation processes before reaching the stratosphere. Substances that are chemically reactive (such as with respect to the hydroxyl (OH) radical) can be transformed in the lower atmosphere. Physical solubility and chemical reactivity both act to shorten the lifetime of the parent

substance in the lower atmosphere. The result is that less of the substance is available for transport into the stratosphere. Long-lived ozone-depleting substances, such as chlorofluorocarbons (CFCs), are not removed by such chemical and physical processes—in other words, they are “survivors” in the lower atmosphere.

- *Once in the stratosphere, the substance must be vulnerable to the release of its halogen atoms.* Two major kinds of processes can alter a substance once it reaches the stratosphere. The first is photolysis, in which the substance is broken apart by the action of sunlight. The stratosphere has a greater abundance of high-energy ultraviolet radiation than the lower atmosphere, so chemical bonds become more susceptible to photolytic breakdown in the stratosphere. The second stratospheric process that releases the halogen atoms of ODSs is chemical reaction. In the stratosphere, reactive radical species can chemically alter the ODS. Multiple-step processes, involving photolysis and/or chemical reactions, are usually involved in the stratospheric release of halogen atoms from ODSs.

### ODP Fundamentals

If a substance reaches the stratosphere, what is its effect on the ozone layer?

The concept of the Ozone Depletion Potential (ODP) has been used as a means of describing the impact of halogen-containing substances on the ozone layer. The ODP is a relative measure that compares the expected impact on ozone per unit mass (e.g., kilogram) emission of a gas to the impact of the same unit mass of CFC-11, integrated over time. The “steady-state” ODP represents the relative amount of ozone destroyed by continued emission of a gas over its entire atmospheric lifetime:

$$\text{Steady-state ODP} = \frac{\text{Global change in ozone due to a unit mass of substance “x”}}{\text{Global change in ozone due to a unit mass of CFC-11}}$$

The ODP is thus a relative measure that does not describe the absolute amount of ozone destroyed by a particular substance. It has been used as a comparative tool to assess the trade-offs associated with various possible substances that might be in use or under consideration for use in human applications.

Complex numerical models are used to evaluate the ODP. The models include representations of atmospheric transport in two dimensions, as well as chemistry that represents dozens of chemical species and hundreds of photochemical reactions. For a particular substance, the evaluation of an ODP requires specific laboratory and field data about the substance for input to the models. For example, the photolysis rate parameter and the OH-reaction rate parameter are required. So, the determination of an ODP for a specific substance is a research endeavor that involves several steps and requires information that may or may not be available in the existing literature for that substance.

The steady-state ODP is most useful for substances with atmospheric lifetimes that are comparable to the reference compound, CFC-11. But when a substance (“x”) has a relatively short atmospheric lifetime compared to CFC-11, the concept of a “time-dependent” ODP often gives a more meaningful picture of near-term effects of the substance. This is because the steady-state ODP compares the calculated steady-state ozone loss due to x, which will be realized in a few years or less, with the centuries-long ozone loss due to the longer-lived CFC-11. For the first decade, for example, substance x will realize a greater fraction of

its total ozone loss. At that point in time, the ozone depletion due to x will be larger than the steady-state ODP suggests. Depending on the substance under consideration, the relative ozone loss at shorter time scales can exceed the steady-state loss by as much as a factor of 10 or more. The time-dependent ODP provides a measure of relative ozone loss over specific time horizons, for example using 5-year intervals to capture the near-term effects.

For well-mixed gases (lifetimes longer than one year), the model-based ODP calculations rely on accurate simulation of stratospheric circulation (which controls the stratospheric distributions of halocarbons and therefore their release of reactive chlorine and bromine) and chemistry. However, the models are not perfect in this. They may, for example, be lacking adequate representation of heterogeneous processes known to be critical to ozone depletion. An alternative to model-based approaches is an empirical approach that uses observations of source gases, considered as tracers of the troposphere-stratosphere exchange processes, to evaluate by comparison how much chlorine or bromine is released from halocarbons. This information is combined with observations of ozone loss to deduce a “semi-empirical” ODP. A series of factors are involved: the lifetime of the ODS ( $\tau_x$ ), the molecular weight ( $M_x$ ), the number of halogen (chlorine or bromine) atoms per molecule ( $n_x$ ), an “ODS-dependent” factor reflecting the release of halogen radicals ( $\beta$ ) from the ODS, and an “ODS-independent” factor describing the relative ozone depletion efficiency for different halogens ( $\alpha$ ). As is the case for other ODP approaches for long-lived compounds, the evaluation is relative to the CFC-11 reference compound:

$$\text{ODP} = \frac{M_{\text{CFC-11}}}{M_x} \times \frac{\tau_x}{\tau_{\text{CFC-11}}} \times \frac{n_x}{3} \times \alpha \times \beta$$

The formulation shows that the ODP is higher for substances that have long lifetimes ( $\tau_x$ ), multiple halogen atoms per molecule ( $n_x$ ), and/or high halogen release factors ( $\beta$ ), as would be expected.

## II. Scientific Issues Regarding the Assessment of Short-Lived Halogenated Substances

The approaches outlined in section I above were developed to determine ODPs of long-lived gases, and the approaches work well for that purpose. For short-lived substances, the classical view cannot be applied for reasons described below. A new approach is needed so that proposed replacement compounds, which often have shorter lifetimes, can be assessed with regard to their effect on ozone depletion.

Accurate determination of the ODP for a halogenated substance depends on:

- (i) quantifying the amount of chlorine or bromine that the substance delivers to the stratosphere, and
- (ii) then determining how this chlorine or bromine, in various forms, affects ozone in the stratosphere.

For short-lived substances, the first of these two steps poses difficulties that are not a hindering factor for long-lived substances. Transport to the stratosphere occurs mainly via the tropical tropopause (i.e., the boundary between the troposphere and the stratosphere). Depending on the latitude/longitude and season of its emission, transport to the tropics could take on the order of several months or a year. Thus, a short-lived substance might undergo

significant loss through tropospheric physical or chemical removal processes before reaching the tropics. For short-lived substances, halogens can then be delivered to the stratosphere in either or both of two ways: (1) via the remaining amount of the original parent substance (pathway A), and/or (2) via the halogen-containing degradation products that have resulted from tropospheric reactions of the parent substance (pathway B). Researchers have suggested that for short-lived substances, pathway B may be dominant (Dvortsov *et al.*, 1999; Ko *et al.*, 1997). Modeling of tropospheric transport processes is thus crucial in evaluations of ozone depletion by short-lived substances.

In contrast, long-lived substances such as CFCs are uniformly mixed in the troposphere and are not transformed by chemical and physical processes in the lower atmosphere. Only pathway A, transfer of the original parent substance, need be considered in this case. It is straightforward to predict how much of the long-lived substance is delivered to the stratosphere. Furthermore, the amount is independent of the season and location of the emission, provided the atmospheric lifetime is longer than several months or a year. The modeling of tropospheric circulation is not a critical factor, and two-dimensional models are usually adequate for evaluating the ODP.

A workshop focused on discussing the stratospheric impacts of short-lived gases was convened on 30-31 March 1999 by the U.S. Environmental Protection Agency and the National Aeronautics and Space Administration. The summary report (Wuebbles and Ko, 1999) expressed the special circumstances of ODPs for short-lived substances as follows:

*“As part of this workshop, it is important to have the perspective on short-lived chemicals relative to long-lived chemicals. The ODP values for the CFCs calculated by the 2-D models are reliable. For most of the hydrogenated halocarbons that react with OH in the troposphere, the same argument applies as long as the lifetime is longer than several months. As the lifetime becomes shorter, one has to worry about the following:*

- *the amount of source gas that survives its journey through the troposphere to be transported to the stratosphere depends on the location and time of the year at which the source gas is released. For this reason, one has to get a better description of the distribution of OH and transport in the troposphere to get reliable answers;*
- *pathway B (see two paragraphs above) may become important and one has to worry about the transport and fate of the degradation products and radicals and keep account of how much is transported to the stratosphere before being removed in the troposphere.”*

The second point is especially challenging, because the reaction pathways and degradation products of short-lived substances are frequently unknown.

The models that have been used to calculate traditional ODPs are zonally averaged two-dimensional models. Such 2-D models cannot capture the tropospheric variations in concentration and transport of short-lived compounds and their degradation products. In the March 1999 workshop cited above (Wuebbles and Ko, 1999), the participants stated that the traditional ODP approaches are not adequate for the case of short-lived substances, and that new three-dimensional modeling approaches and a modified approach to the ODP need to be considered for such compounds.

### III. Update of Research on the ODPs of Short-Lived Substances

Since the publication of the 1998 assessment report of the Science Panel (WMO, 1999), the research community has conducted new research on the topic of ODPs of short-lived substances. All of the studies have pointed out that the amount of halogens delivered to the stratosphere by a short-lived substance depends on the season and the place (latitude/longitude) of its emission. Both of these factors affect the amount of the parent compound plus degradation products that reaches tropical latitudes, the primary site of entry into the stratosphere. The result is that the ODP of a short-lived compound cannot be viewed as an intrinsic property of the substance that is equally applicable worldwide. Rather, a concept of an “ODP matrix” has been suggested, whereby the ODP value is calculated and tabulated as a function of latitude/longitude of emission and time of emission. For a given substance, research has shown that the ODPs in the matrix can vary by more than an order of magnitude.

A few studies have used this new approach to provide assessments of the ozone-depleting potential of n-propyl bromide (also referred to as 1-bromopropane,  $\text{CH}_2\text{BrCH}_2\text{CH}_3$ , or simplified as 1-C<sub>3</sub>H<sub>7</sub>Br or nPB). This particular substance, which has been commercialized as a solvent, has an estimated atmospheric lifetime of ~11 to 14 days (Nelson *et al.*, 1997; Wuebbles *et al.*, 1998, 1999), depending on the atmospheric chemistry associated with the region in which it is emitted. Bromine is, on a per-atom basis, about 40 times more active than chlorine in destroying ozone, and we presently have larger uncertainties in the stratospheric bromine budget as compared to chlorine. Thus, national and international decisionmaking bodies are seeking scientific guidance on evaluating the possible effects of nPB on the ozone layer. We summarize here the studies to date. While the results are specific to nPB, the general features of the results are likely very indicative of the results for other compounds that are similarly short lived. The research on such short-lived compounds is new and evolving. Hence, the results summarized here are preliminary.

D.J. Wuebbles, K.O. Patten, M.T. Johnson, and R. Kotamarthi, “Progress in Evaluating Ozone Depletion Potentials for n-Propyl Bromide as a Function of Location of Emission”

(NOTE: This study is still in progress.)

Wuebbles *et al.* used two- and three-dimensional chemistry-transport models to examine the potential effects of nPB on stratospheric ozone. The degradation chemistry of nPB was fully considered by referencing specific studies of reaction rates (such as OH + nPB) or (for the many instances that have not been specifically studied) by analogy with known reactions that are similar. The consideration of detailed nPB chemistry led to the incorporation of an additional 255 photochemical reactions and 81 new species in the model. Of the bromine added to the stratosphere from nPB, only 10% was contributed in the form of nPB. By far the greatest nPB-caused change in total stratospheric bromine was found to arise from the inorganic bromine that is produced from nPB degradation.

A 3-D model was used to evaluate four geographic scenarios of nPB emission: (1) global (60°S-70°N); (2) North America; (3) North America, Europe, China, Japan; and (4) India, Southeast Asia, Indonesia. The model applied the full degradation chemistry in calculating the burden of nPB and its degradation products at the tropopause for each geographic emission scenario. This burden was then used in a scaling factor to adjust the ODP calculated from a 2-D model. (Alternatively, the burden at the stratosphere was

investigated as the scaling factor.) As expected, because of proximity to the region of stratospheric entry, the ODP was largest (0.098-0.111) for the tropical emissions scenario (India, Southeast Asia, Indonesia). Emission from North America yielded the smallest ODP, 0.020-0.021. Thus, the ODP values ranged over about a factor of 5 for the emissions regions that were studied.

S.C. Olsen, B.J. Hannegan, X. Zhu, and M. Prather, "Evaluating Ozone Depletion from Very Short-lived Halocarbons"

Olsen *et al.* also applied a three-dimensional chemistry-transport model to calculate the amount of short-lived ODS delivered to the tropical tropopause (used as a surrogate measure of transport into the stratosphere) for various seasons and latitudes of emission. The resulting ODP was found to vary by factors of 100 or more for various seasons and latitudes of emission. For nPB, the ODP ranged from 0.0002 (for summer emissions at northern latitudes) to 0.06 (for tropical emissions). These ODP values are smaller, particularly for the extratropical emissions, than those found by Wuebbles *et al.* A possible contributing factor is that Olsen *et al.*'s calculation of ODPs did not include the impact of possible bromine-containing nPB degradation products, which Wuebbles *et al.* propose as providing about 90% of the incremental bromine from nPB to the stratosphere. Differences in the modeling of tropospheric transport could also contribute to the ODP outcomes.

C.H. Bridgeman, J.A. Pyle, and D.E. Shallcross, "A Three-Dimensional Model Calculation of the Ozone Depletion Potential of 1-Bromopropane (1-C<sub>3</sub>H<sub>7</sub>Br)"

Bridgeman *et al.* used an empirical approach to the calculation of ODPs, whereby the ODP of a compound depends mainly on its calculated lifetime and the fraction of its emissions that reach the stratosphere. A three-dimensional model was used to evaluate the ODPs as a function of latitude and season of emission. For nPB, the authors found that these factors cause the annual averaged ODP values to vary by a factor of ~3 (0.0033 to 0.0109). As expected, results showed that emitting nPB in the tropics was more effective in transporting bromine to the stratosphere. Bridgeman *et al.* show that the ODPs are also very dependent on assumptions and methods used to calculate lifetime and the fraction released in the stratosphere. Under other assumptions, the range of calculated ODPs for nPB increases to factors of 30 or more.

As in the study by Olsen *et al.*, calculated ODPs of Bridgeman *et al.* reflect transport of only the parent nPB compound to the stratosphere. Bridgeman *et al.* explore potential sensitivity to transport of nPB degradation products to the stratosphere. From their analysis of possible degradation schemes, Bridgeman *et al.* find that it is possible that brominated degradation products reach the stratosphere. They point out that calculated ODP values could be much larger in that case. In the tropics, for example, the stratospheric bromine burden from nPB increases by about a factor of three if degradation products are considered.

Summary of Findings from Recent Research

All three of the most recent studies have found that for short-lived compounds, it is not possible to describe a single value of the ODP. Season and place of emission are factors that can cause large variations in the amount of a short-lived substance reaching the stratosphere, thereby affecting the impact of the substance on the ozone layer. The studies all used three-dimensional models to estimate ODPs, but each investigation used a different

approach to arrive at values for the ODPs. Degradation chemistry was investigated in some detail in only one study, though all three papers acknowledge the critical effects of this chemistry on the calculated ODP.

Even with the significant common ground noted above, the studies have arrived at a range of ODP values for the case of nPB:

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<u>Study</u>	<u>ODP range</u> <sup>*</sup>	<u>Effects of degradation chemistry included in ODP range?</u>
Wuebbles <i>et al.</i> <sup>**</sup>	0.020 - 0.111	yes
Olsen <i>et al.</i>	0.0002 - 0.06	no
Bridgeman <i>et al.</i>	0.0033 - 0.0109	no

\* Range for one set of calculation assumptions in the paper. The authors also examined other sets of assumptions that resulted in different ranges of ODPs.

\*\* Study still in progress.

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In addition to differences in the specific 3-D models and the modeling approaches used in the studies, the three studies differed with respect to their treatment of nPB degradation chemistry. Current knowledge is incomplete with respect to (i) the products formed from nPB degradation and (ii) the delivery and release of halogen to the stratosphere by degradation products. These uncertainties propagate significant uncertainty into the estimates of the ODP and explain some of the differences in the results of the three studies. Differences can be further explained by the variation in treatment of transport in the models.

#### **IV. Outstanding Research Issues and Their Relation to Policy Needs**

Recent research has firmly established that short-lived compounds would be inaccurately described by a single “traditional” ODP value. Though three studies have used very different approaches to estimate the ODPs for short-lived compounds, the studies have all indicated that the ODP is latitude dependent and seasonally variable. This shows a foundation for agreement among researchers.

Lack of observations and further supporting theoretical information prevent clearly favoring one set of results over the other. But by analyzing a common “test case” for nPB, the three studies revealed that the results for the ODP can vary by factors of 30 or more, depending on the approach to the calculation. Thus, the details of applying new approaches to evaluate ODPs are far from converging at this point in time. Each study has acknowledged significant uncertainties in the assumptions made in their approaches and, to illustrate, the authors present results using alternative assumptions. Furthermore, the degradation chemistry is often estimated by analogy because studies of the specific reactions of interest do not exist. Observational datasets for compounds of interest are often sparse or nonexistent.

## Scientific Approaches of Possible Relevance to Policy Needs

Thus far, international agreements to protect the ozone layer have relied on single-value ODPs that can be applied uniformly worldwide. This report has shown why this approach is not viable in the case of short-lived substances. We describe two examples of scientific capabilities that might prove useful to the Parties in their considerations of short-lived substances.

### *1. Geographically-dependent ODPs*

The state of science is such that, at this point in time, the scientific community is developing some first capabilities to provide a table of estimated, geographically-dependent ODPs for short-lived substances. The pioneering case studies of nPB have demonstrated that the range of ODPs in such a table could span even two or more orders of magnitude, an outcome that illustrates both the extreme sensitivity of the ODPs to season/latitude of emission and the early developmental stage of the models that are being used to estimate the ODPs. The table of geographically-dependent ODPs, and/or the range of ODPs, could prove useful to the Parties.

### *2. Halocarbon scenarios*

The scientific community could provide an alternative type of analysis of short-lived compounds that goes beyond the comparative “per-kilogram” ODP concept and includes an estimate of the compound’s potential emissions. Namely, three-dimensional models could be applied to evaluate the contribution of the short-lived substances to stratospheric halogen loading, from the present to, say, 2050. The evaluation could use estimates by the Technology and Economic Assessment Panel of the potential emissions by region and by season. The resulting increment to halogen loading could then be compared to contributions to the stratospheric halogen burden from other factors that are given in the halocarbon scenarios of the science assessment (such as accelerated phaseout of methyl bromide, or alteration in permitted essential uses, as have been evaluated in past Scientific Assessment Reports). This approach would give a practical way to put the ozone-depletion effects of short-lived substances into perspective with other halocarbon scenarios and past major choices. Although it would represent a departure from the previous practice of using ODPs as the yardstick for decisionmaking on specific compounds, the concepts of potential stratospheric halogen loading and halocarbon scenarios have been used throughout the assessment process and are familiar to the Parties. Like the ODP, which is a measure that is relative (to CFC-11), the potential stratospheric halogen loading and halocarbon scenarios can be compared with one another to assess their relative contributions to ozone-layer protection. The halocarbon scenarios for short-lived compounds specify the amount of emissions and would, like the ODPs, also depend on the location and season of emissions.

## Interactions of the Parties with the Science Assessment Panel and the Scientific Community with Regard to Evaluations of Short-Lived Substances

*Significant uncertainties remain in the process of evaluating ozone depletion by short-lived substances.* This report illustrates that assessing the ozone impacts of short-lived substances is an active area of research that is still in its infancy. The scientific community has developed some initial approaches to address the scientific challenges, but first results for nPB indicate that the results can vary widely among researchers. This is because there are many uncertainties regarding the degradation chemistry in the lower atmosphere, as well as in the set of assumptions used to specify the lifetime, transport, and fate of the parent compound

and its degradation products. The three-dimensional models used in the research on short-lived substances are still in development and in most cases do not fully represent the necessary chemistry and transport processes throughout the troposphere and stratosphere. All in the scientific and decisionmaking communities therefore should be cognizant of the limitations and uncertainties in assessments of short-lived substances.

*Evaluation of the ozone impact of a newly proposed short-lived substance is a more complex and expensive research endeavor than past evaluations of long-lived substances.* This report makes it clear that each proposed new substance is a “scientific unknown” with respect to its ozone-layer impacts. Assessment of potential effects of a short-lived substance will require new research in every case. As described, computationally-intense 3-D models are needed to address the special scientific issues related to short-lived substances. Degradation chemistry is usually unknown and requires that new laboratory studies be conducted. In sum, the evaluation of the ODP of long-lived substances has been a fairly straightforward calculation. In contrast, a measure of the ozone-depleting potential of a new short-lived compound is a much more complex, lengthy, and expensive research endeavor.

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