STRATOSPHERE OZONE PROBLEM AND SPACE ACTIVITY

by

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Abstract

Humans have demonstrated a remarkable capacity to threaten Mother Earth's natural environment. Pollutants, contaminants, rogue nuclear substances, and debris have accompanied humans upon their entry into outer space. Concern exists over the environmental problems resulting from the use of rocket fuels. Attention has been directed to the need to protect the ozone layer from a variety of chemical reactions.

This study calls for further investigations into the effects of fuel uses and the formation of international norms designed to protect against environmental detriment and decay. Account is taken of the importance of successful space activities. National responsibilities are indicated.

Introduction

1992 provides a remarkable opportunity to improve on basic commitments to environmental security. Humans are responding to the challenges to their shared biosphere. The 1992 UN Conference on Environment and Development (UNCED) asserted that there must be a more caring and a more careful use of the Earth's resources.156.[1] It calls for a wide-ranging distribution of the benefits as well as the risks of our scientific and technological civilization. The serious and committed efforts of the past must be extended and enlarged.[2]

Today a fundamental policy issue must be confronted. It is a matter of risk. The questions are: Will excessive environmental controls limit important progress? What is "excessive"? How extensive can such controls be in the absence of ultimate factual assessments? In sum, in measuring the element of risk there is the possibility that inadequate controls would produce long-term impairments of the human environment. Also to be considered is the difficulty of eliminating improvident controls when it is discovered that supposed dangers were not so real as originally perceived.

Faced with this dilemma UNCED urged preventive actions. It's Principle 15 provided: "In order to protect the environment, the precautionary approach shall be widely applied by states according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation."[3]

This is sensible and creative counsel. Although not unconditional, it highlighted the role of states in the prevention of environmental degradation. As such it must be seen as an improvement over the highly important Principle 21 of the 1972 UN Conference on the Human Environment, which provided: "States have, in accordance with the Charter of the United Nations and the principles of international law, the sovereign right to exploit their own resources pursuant to their own environmental policies, and the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other Sates or of areas beyond the limits of national jurisdiction."[4]

The nature of the risk is best understood in the widest context. One writer, whose focus has been on the environmental issues raised by harms to the Earth's ozone layer, has identified major areas of concern. In his view researchers need to go "far beyond atmospheric chemistry; they [have] to examine the planet as a system of interrelated physical, chemical, and biological processes taking place on land, in water, and in the atmosphere, processes that are themselves influenced by economic, political, and social forces."[5]

Essential Scientific Facts

The 1972 Stockholm principles were fashioned in order to respond to the perceived phenomena of the time. These concerns focused on pollution of the oceans, acid rain, transboundary air pollution, global warming, and especially on the greenhouse effect of hydrocarbons. More recently concerns have arisen about equally important hazards. These include the solid debris of non-functional satellites. The presence of nuclear waste, the military or other hostile use of environmental modification techniques,[6] the ozone-depleting effects of chloroflourocarbons on the atmosphere (CFC 11, 12, 113, 114, and 115), used in many Earth-based industries to clean precision electronic, mechanical, and optical components, halons (1211, 1301, and 2402), carbon tetrachloride (CC14), methyl chloroform, used in metal cleaning and degreasing operations, and the chemical reactions between the atmosphere and the fuel sources (both liquid and solid) which have supplied power for the launch of space objects and non-orbiting rockets.

In the United States that Space Shuttle and the Titan-4 launcher are the largest users of solid fuels. In Europe the Ariane 5 employs solid fuels. These fuels consist of an ammonium perchlorate oxidizer (NH_4ClO_4) and a polymer fuel (the propellant binder) loaded with powdered aluminum. "The principal effluents are hydrogen chloride (HCl), aluminum oxide (Al_2O_3), water (H_2O), hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2)."[7] Nitrogen (N_2) as well as trace amounts of metals and organics appear in launch exhausts.[8] The aluminum oxide component consists of solid alumina particles.[9]

Each Shuttle launch vehicle uses about 1,000 tons of solid propellant and about 730 tons of liquid propellant.[10] In assessing the adverse effects of rocket fuels on the environment, it is necessary to identify areas, amounts, and duration of effluents. The troposphere extends from the surface of the Earth upwards for about 8 km, the stratosphere from 8 to 50 km, and the mesosphere from 50 to 67 km. Above this is the thermosphere or ionosphere which reaches up to about 450 km where the exosphere begins. The atmosphere reaches into the exosphere, although there is no agreed distance above the surface of the Earth for the atmosphere. The ozone layer is found at about 18-50 km above the surface of the Earth.

The impact of the ozone depleting capability of chlorine-based fuels depends on "how much of each compound is introduced at various altitudes, reaction rates, which depend on temperature, pressure, relative concentrations and residence times; and, how quickly harmful constituents are transported out of the stratosphere."[11]

The effluents of the solid fuels are disseminated below 50 km. According to one study, about twice as many kilograms of chlorine will be released at 15-20 km than at 30-35 km and about 40 times as much at 15-20 km than at 45-50 km. Less will be released at 20-25 km than at 15-20 km.[12] Since the ozone layer resides at about 18 km above the Earth's surface about 24% of the chlorine effluent would enter the ozone layer. Detriment would be substantial. The balance would be released at altitudes higher than 20 km.

Liquid propellants are also required for space launches. "The three liquid propellant combinations most commonly in use are liquid oxygen/hydrocarbon [kerosene], nitrogen tetroxide used with a mixture of unsymmetrical dimethylhydrazine and hydrazine [aerozine], and liquid oxygen/liquid hydrogen."[13] The exhaust products of the liquid fuels for the Shuttle's main engine consist of hydrogen gas and water; those for a Titan-4 are carbon monoxide, carbon dioxide, hydrogen gas, water, and nitrogen.[14] The systems using kerosene "will also emit CO, CO_2, and N_2. Both solid and liquid systems also form oxides of nitrogen, NO_x (e.g., NO or NO_2), as hot exhaust products react with N_2 in the atmosphere."[15] The effluents from liquid fuels "are primarily injected above 50 km."[16]

Experts in atmospheric chemistry have attempted to quantify the amount of chlorine introduced into the atmosphere through the employment of solid rocket and liquid rocket fuels. A variety of assumptions and different models have been employed. Two major conclusions can be drawn. The chlorine used in launches does produce harms to the ozone layer. It contributes to other major adverse ozone-depleting activities. Second, efforts, such as a next generation launcher, identified as the National Launch System (NLS), to minimize the adverse effects of fuels reliant on chlorine, would probably employ a common liquid propulsion system.[17] Further, there are a variety of known propellant options which could reduce the existing adverse environmental impact of large chlorine uses. These options, if successful, would reduce acid rain, ozone depletion, toxity, and the production of aluminum particulates and ice.[18]

Manifestly, the success of space programs and activities depends on the avoidance of unacceptable environmental hazards. This means that all manufacturers of chlorine-based products and the users of such materials must cooperate in the minimization of prospective harms. Representative of such concerns is the position of the Du

Pont Corporation, a long-time and major producer of CFC. In 1991 the Company reported that in 1992 its CFC production would be "less than half the level produced in 1986 and substantially below the levels permitted by the Montreal Protocol and the U.S. Clean Air Act. We would cease production of CFCs immediately if substitute products and equipment were broadly available to make it practical to do so. [Further, the Company stated that it was] committed to phase out CFC production in the United States and other developed countries no later than the end of 1995."[19]

International and National Legal Responses

The principal international agreements dealing with such ozone depleting chemicals as CFC, halons, carbon tetrachloride, and methyl chloroform are the March 22, 1985 Vienna Convention for the Protection of the Ozone Layer,[20] the September 16, 1987 Montreal Protocol on Substances that Deplete the Ozone Layer,[21] the May 2, 1989 Helsinki Declaration on Protection of the Ozone Layer,[22] and the June 29 1990 London Adjustments and Amendments to the Montreal Protocol on Substances that Deplete the Ozone Layer.[23]

In the United States both before and following these agreements, legislation was adopted seeking to improve the human environment. Most recently it has been directed specifically at the foregoing ozone depleting chemicals. The U.S. Clean Air Act, originally adopted in 1955, was completely revised in 1977.[24] Since then it has been amended many times. The statute requiring protection of stratospheric ozone was adopted on November 15, 1990.[25] It designated, by year, the substances which must be phased out pursuant to the Montreal protocol.[26] In the United States there has been involvement on the part of the Environmental Protection Agency, the Departments of State, Defense and Transportation, the White House Council on Environmental Quality, NASA, and the Congressional Office of Technology Assessment. The governments of many of the states have also adopted environmentally oriented legislation.

Non-governmental bodies have issued vigorous demands that substantial efforts be made to minimize environmental hazards. In their concern for the chlorine depleting impact on the ozone layer they have not overlooked the respective roles of solid and liquid rocket fuels. Among those actively engaged in the finding of facts and in the establishment of policies have been the Environmental Defense Fund, the National Toxics Campaign Fund, scientific groups such as the Federation of American Scientists, as well as business entities and technical advisers.[27]

The Need for Continuing Research

Leading experts concluded in 1991 that there was no present need to use new rocket fuels in order to safeguard the environment. They stated: "Based on careful evaluation of scientific studies performed in the United States, Europe, and the Soviet Union, the workshop concluded that the effects of rocket propulsion on stratospheric ozone depletion, acid rain, toxicity, air quality, and global warming were extremely small compared to other anthropogenic impacts, and therefore that there is no pressing need to change the propellants of current launch systems."[28]

Without endeavoring to assess the comparative contributions of rocket launches (using both solid and liquid fuels) and other sources of ozone depleting chemicals, it is evident that all produce and disseminate chlorine residues in the stratosphere and beyond. This suggests the need for all concerned to take all appropriate steps, based on immediate self-interest and the larger interest of the entire community, to mitigate and, over time, to eliminate basic threats to the health of the ozone layer and to the plant and animal life which require the protective influences of the ozone layer.

Alternatives

The present international legal regime, going back to the 1985 Vienna Convention, mandates that States engage in research and make scientific assessments relating to ozone depletion.[29] Among the subjects to be considered are alternative substances and technologies. The systematic research and observations apply particularly to carbon substances, nitrogen, chlorine, bromine, and hydrogen.[30] The acquired data is to be shared.

On the basis of these obligations States, private entities, including proponents of environmental security, have engaged in investigations and have disseminated their findings. Attention has been given to chemicals, including CFCs, halons, carbon tetrochloride, and methyl chloroform. Attention has also been given to launching methodologies, the size of rockets, and new rocket fuels.

In the United States steps have been taken to develope an Advanced Launch System utilizing new technologies.[31] In an analysis of the U.S. Space Exploration Initiative attention was given to supporting technologies. Development was suggested respecting nuclear thermal propulsion, lightweight structural materials, and nuclear electric propulation for follow-on cargo missions.[32]

With the winding down of the Cold War the U.S. government is converting Titan II rockets to space launch purposes. In the process the rockets' liquid engines are being refurbished and off-the-shelf solid fuel rocket boosters will be employed.[33] This comports with the proposition that hybrid fuels can be more friendly to the atmosphere. Titan IIs are smaller than the Shuttle and Titan-4s and the amount of effluent will be less.

Moreover, it may be possible to substitute gel propellants for existing solid and liquid propellants. Scientific support for this propellant is based on the conclusion that "the combined safety, handling, storage, and environmental characteristics of gelled propellants are better than either liquids or solids."[34] Gel propellants are cheaper and safer than both solid and liquid propellants.

The case for safety has called attention to hybrid fuels. Thus, "[to] operate liquid rockets safely, particular care must be taken to keep separate the two liquids, usually cryogenic oxygen and hydrogen, that could explode if mixed inadvertently. Hybrids have only the easier of the two, liquid oxygen, to contain, and in any case, without hydrogen present, leaks are less dangerous and less likely to occur."[35] Hybrids are also considered to be more reliable than solid propellants.[36] There is increasing support for the use of hybrid and liquid fuels.[37]

In the United States the National Launch System program is experimenting with cleaner and more environmentally compatible solid rocket propellants for future space launches. Research is being conducted respecting chlorine-free hydroxyl ammonium-nitrate compositions, sodium-nitrate scavenged formulations, and others in which magnesium is substituted for aluminum fuel.[38]

Aluminum as a Solid Rocket Fuel Source

Aluminum is used as fuel in virtually all solid rocket propellants. Both with and without afterburning a major exhaust product is aluminum oxide (Al_2O_3).[39] This exhaust "has the potential to perturb stratospheric chemistry."[40]

The alumina particles form a radii greater than 1 micron and are perceived as a very fine powder hardly visible to the naked eye.[41] The stratospheric abundance of larger alumina particles "appears to be increasing and has been attributed to solid rocket motors as well as space debris."[42]

Following the burning of solid fuels the aluminum effluents are found above 12 km. There has been an apparent tenfold increase from 1976 to 1986.[43]

The participants at the June, 1991 AIAA Workshop estimated on the basis of one launch of an Atlas II AS Shuttle, Delta II, and Titan-4 that the United States would produce 404 tons of aluminum exhaust product, Europe (Ariane 5) 132.1 tons, and Japan 61.9 tons.[44] If it were to be assumed that the United States would launch 36 space objects annually until 2000, that the Europeans would launch 5 annually, and the Japanese a total of two annually, this would produce 6,931 tons of aluminum effluents.[45]

The concentration of aluminum oxide varies according to altitude. In a detailed study of the exhaust products from the space shuttle by atmospheric layer (kilograms per launch), it has been reported that at 0 to 500 metres there were 39,284 killograms of aluminum oxide; at 0.5 to 13 km (troposphere), 26,385 kg; at 13 to 50 km (stratosphere), 110,304 kg.; and nothing at higher altitudes. The amount of aluminum oxide effluent was somewhat greater than the amount of hydrogen chloride, less than chlorine and nitric oxide, but greater than water and carbon dioxide.[46] Unlike hydrogen chloride with its harmful effect on the ozone layer, aluminum oxide can be converted into aluminum chloride, which as a toxic irritant, can affect the mucous membranes. Aluminum oxide, on the other hand, "can serve as a nucleation site for the condensation of hydrochloric acid, increasing acidity at ground level."[47] The impact of aluminum effluents on environmental security is undergoing scientific study through laboratory models.

While at present "not much is known about the possible effects of these particular exhaust particulates on heterogeneous ozone chemistry,"[48] it has been suggested that "particulates released by the rockets themselves may chemically react with ozone . . . ."[49] However, it has also been pointed out that hydrogen chloride gas, with its harmful effects on the ozone layer, can be removed as a threat by replacing hydrogen chloride with aluminum and ammonium nitrate fuel.[50] This new fuel combination would produce aluminum oxide particulate emissions. It has been suggested that before moving in this direction it will be necessary to consider "the impact on ozone depleting heterogenous reactions as well as tropospheric and boundary layer effects."[51] One can be encouraged by the fact that serious studies are being made to clarify what the adverse environmental impact, if any, may be on an enhanced use of aluminium as a source of rocket fuels.

Conclusion

The health of our shared biosphere will depend on accepting basic facts and taking appropriate action. The United Nations was correct in its 1989 assessment when it referred to the "continuing deterioration of the state of the environment and the serious degradation of the global life-support systems, as well as . . . trends that, if allowed to continue could disrupt the global ecological balance, jeopardize the life-sustaining qualities of the Earth and lead to an ecological catastrophe."[52]

It is evident that chlorine and quite possibly aluminum-based fuels have a harmful effect (as do other chlorine-based compounds used for other purposes) in the Earth's ozone layer. Since the problem is, by its very nature, multidimensional and global, corrective action will depend on multinational and multidisciplinary responses.

The efforts to secure propellants of an environmentally neutral nature are wide-ranging. Private firms are taking many initiatives. National governments and international intergovernmental, as well as private international groups of scientists, have embarked on research activities. Attention is also being given to improving the characteristics of rocket motors, as in the case of the U.S. Air Force's Solid Rocket Motor Upgrade and the new Ariane 5 solid rocket booster. At the international institutional level leadership is being exercised at the United Nations, at the UN Development Program, at the World Meterological Organization, and at the Committee on Space Research. The International Astronautical Federation is also giving wide-ranging attention to the situation.[53]

Means exist to reduce the amount of chlorine employed in the launch aspects of outer space activities as well as in Earth-based activities. The antipollutional and positive interest in protecting the Earth's ozone layer can be manifested in numerous ways.

Requiring study are such subjects as the chemical reactions between rocket fuels (solid and liquid) and the ozone layer, prospects for gel fuels, qualitative improvements in rockets and launching systems, relationship between civil and military rocket requirements, habits respecting consumption of environmentally deleterious products in both the advanced and developing countries, impediments to economic development, and population growth. New, alternative, and imaginative approaches must be brought to these and other relevant problems. Only an integrated approach will have any chance of success.

The enforcement activities of States in carrying out the 1992 Rio Principles will be decisive in future successes of outer space activities. Risk is entailed in even the most carefully planned approach. Whatever the risks they must be shared by both the advanced and the developing nations. Any implemented policy must be reviewed constantly so that it can be terminated in the event that, on a cost-benefit assessment, there are indications that pursuing the policy will result in greater detriment than advantage. Formal understandings should exist as to how and when an active policy or program is to be terminated.

To this end there must be a firm political commitment with all of the accommodations entailed in such an approach. Pragmatic steps, consistenly supported, which may be slower than grand but speculative approaches, will have a chance to succeed. Diligent and objective testing and modeling will be necessitated. The goal should be consistent with the privately promulgated 1989 Valdez Principles.[54]

Space activity is of vital importance to the well-being of humans and the environment of the universe. As we stated some years ago: "It would be somewhat ironic if the Space Shuttle and other space objects, which have the capacity to serve as a means to assist in the gathering of data relating to the condition of the atmosphere, were to constitute a source of environmental deterioration."[55] Support should be given to all who are seeking to avoid such a condition and who see the value of man's presence and influence in space.

NOTES

1. Among the agenda items were the environmentally sound management of biotechnology and hazardous wastes, including toxic chemicals and protection of the atmosphere including climate changes, depletion of the ozone layer, and transboundary air pollution. *Report of the Preparatory Committee for the United Nations Conference on Environment and Development*, U.N. GAOR, 46th Sess., Supp. 48 at 31, U.N. Doc. A/46/48, pt. I (1991). It is evident that "in the future national and international laws will profoundly influence decisions on the use and choice of chemical rocket systems, as will economic considerations of launch activities." *Atmospheric Effects of Chemical Rocket Propulsion*, Report of an AIAA Workshop, Sacramento, CA, 28-29 June 1991, 26 (Oct. 1, 1991).

2. A vast literature has appeared on the subject. Writing from an international legal perspective have been: C.Q. Christol, *The International Legal and Institutional Aspects of the Stratosphere Ozone Problem* (1975); G. Handl and R.E. Lutz, II, eds., *Transforming Hazardous Technologies and Substances* (1989); S. Johnson and G. Corcelle, *The Environmental Policy of the European Communities* (1989); A. Kiss and D. Shelton, *International Environmental Law* (1991); V.P. Nanda and J.A. Carver Jr., *International Environmental Law and Policy* (1992); A.S. Timoshenko, *International Environmental Law: Evolving Legal Responses to Global Challenges* (1992); E.B. Weiss, P.C. Szasz, and D.B. Macgraw, *International Environmental Law: Basic Instruments and References* (1991); *L'Atmosphere Moyenne et les Observations Spatiales, CNES* (1990). Relevant journal articles are C.Q. Christol, "Aircraft and the International Legal and Institutional Aspects

of the Stratospheric Ozone Problem," 1 *Annals of Air & Space L.*3 (1976); C.Q. Christol, "Stratospheric Ozone, Space Objects and International Environmental Law," 4 *J. Space L.* 23 (1976); J.F. Galloway, "International Law and the Protection of the Ozone Layer," *Proceedings of the 31st Colloquium on the Law of Outer Space* 274 (1989); J.F. Galloway, "Mission to the Atmosphere," *Proceedings of the 32nd Colloquium on the Law of Outer Space* 89 (1990); J.F. Galloway, "Protecting the Ozone Layer: The 1990 London Revision to the Montreal Protocol," *Proceedings of the 34th Colloquium on the Law of Outer Space* 177 (1992); J.W. Kindt and S.P. Minifee, "The Vexing Problem of Ozone Depletion in International Environmental Law and Policy," 25 *Texas Int'l J.* 261 (1989); L.B. Talbot, "Recent Developments in the Montreal Protocol on Substances that Deplete the Ozone Layer: The June 1990 Meeting and Beyond," 26 *The Int'l Law.* 145 (No. 1, 1992); G. Palmer, "New Ways to Make International Environmental Law," 87 *A.J.I.L.* 259 (1992); D. Popescue, "The Draft Convention on Global Environment Protection and Outer Space Conservation," *Proceedings of the 34th Colloquium on the Law of Outer Space* 298 (1992); S.M. Williams, "CFCs and Stratospheric Ozone - Legal and Political Measures," *Proceedings of the 33rd Colloquium on the Law of Outer Space* 177 (1991); S.M. Williams, "The Protection of the Ozone Layer in Contemporary International Law," 10 *Int'l Relns* 167 (Nov. 1990).

3. 20 *Development Forum* 14, No. 3 (May-June 1992). J. Cameron and J. Abouchar, "The Precautionary Principle: A Fundamental Principle of Law and Policy for Protection of the Environment," 14 *B. C. Int'l & Comp. L. Rev.* 1 (1991).

4. U.N. Doc. A/CONF.48/14 and Corr. 1; 11 *I. L. M.*1420 (Nov. 1972). The U.N. General Assembly later affirmed the Principles adopted at the 1972 Conference. This principle became Principle 2 of the 1992 Conference, with the addition after "environmental" of the words "and developmental." C.E. Di Leva, "Trends in International Environmental Law: A Field with Increasing Influence," 21 *ELR* 10016 (February 1991).

5. R.E. Benedick, *Ozone Diplomacy* 13 (1991). He also has observed that "Governments may have to act while there is still uncertainty, responsibly balancing the risks and costs of acting or not acting." *Id.* at 204.

6. A 1976 treaty on this subject entered into force in 1978. 31 UST 333, TIAS 9614. Over 60 parties including the United States are bound by this agreement.

7. *Supra*, note 1 at 16.

8. J.D. Moteff, "Rockets and Ozone: Should Alternative Technologies be Developed?" Congressional Research Service, The Library of Congress, Washington, D.C., CRS-3 (November 22, 1991).

9. *Ibid.*

10. R.R. Bennett and J.C. Hinshaw,

"The Effects of Chemical Propulsion on the Stratospheric Ozone," Internal Report, Thikol Corporation, Brigham City, UT (1991). Cited in R.S. Harwood, C.H. Jackman, I.L. Karol, and L.X. Qui, "Predicted Rocket and Shuttle Effects on Stratospheric Ozone," Chapter 10, *Scientific Assessment of Ozone Depletion*, 1991, Preprint 10-2 (December 17, 1991); R.R. Bennett, J.C. Hinshaw, M.W. Barnes, "The Effects of Chemical Propulsion on the Environment," IAA paper 91-597 at 1 (October 1991). See also 1992 COSPAR papers by Allan J. McDonald, "Assessment of Stratospheric Ozone Depletion by Chemical Rockets," P.2-M.1.03 dated September 2, 1992, and by Robert R. Bennett, "The Atmospheric Impact of 'Clean' Propellants," P.2-M.1.04 dated September 2, 1992.

11. Moteff, *supra*, note 8 at CRS-8. See also S. Aftergood, "Poisoned Plumes," *New Scientist* 34 (Sept. 7, 1991).

12. M.J. Prather, M.M. Garcia, A.R. Douglass, C.H. Jackman, M.K.W. Ko and N.D. Sze, "The Space Shuttle's Impact on the Stratosphere," *J. Geophys. Res.* (D11), 18,584 (1990).

13. *Supra*, note 1, at 21.

14. *Id.* at 24.

15. Moteff, *supra*, note 8, at CRS-3.

16. Harwood and others, *supra*, note 10, at 10-2.

17. *Supra*, note 1 at 16-17.

18. *Id.*, Table 5 at 20.

19. *Dupont Annual Report*, 1991, at 25. In June, 1990, Dupont announced plans for the construction in the United States, Japan, and the Netherlands of four hydroflourocarbon manufacturing facilities. HCFC will replace CFCs in refrigeration equipment.

20. 26 *I.L.M.* 1516 November 1987).

21. 26 *I.L.M.* 1514 (November 1987).

22. 28 *IL.LM.* 1335 (September 1989).

23. 30 *I.L.M.* 537 (March 1991).

24. 42 U.S.C. #7401, Pub. L. 95-95, 91 Stat. 685).

25. 42 U.S.C. #7671, Pub. L. 101-549, 104 Stat. 2649.

26. The basic U.S. legislation is the National Environmental Policy Act of 1969. 42 U.S.C. #4321, Pub. L. 91-190, 83 Stat. 852.

27. I have benefitted in my understanding of both scientific and policy issues from information provided by Steven Aftergood, R. Bender, William Bjorndahl, Bruce A. Brown, Daniel P. Byrnes, Jonathan F. Galloway, John L. Guldiman, Theodore R. Harper, William E. Haynes, Charles H. Jackson, Valerie Lang, Allan J. McDonald, Lenny Siegel, Wayne N. White, Jr., and Paul Zittel.

28. *Supra*, note 1, at 1. J.L. Karol, Y.E. Ozolin, and E.V. Rozanov, "Effect of Space Rocket Launches on Ozone and other Atmospheric Cases," made public on April 20, 1991. They called for additional "observations

and measurements in the rocket exhaust jets and around the launching domain," especially regarding "the aerosol effects on ozone," p. 7.

29. *Supra*, note 20, at 1530. Article 3.

30. *Ibid.*, Annex I.

31. "Executive Summary of the Report of the Advisory Committee on the Future of the US Space Program" [the Augustine Report], 7 *Sp. Policy* 176, No. 2 (May 1991). For a recent assessment see J. Grey, "Ups and Downs of the New Space Launcher," 32 *Aerospace America* 26, No. 6 (June 1992).

32. The Synthesis Group, "America at the Threshold" [the Stafford Report], 7 *Sp. Policy* 261, No. 3 (August 1991). See also "Focus, New Directions in Propulsion '92," 30 *Aerospace America* 21, No. 7 (July 1992).

33. R. Piellsich, "Recycling an Arsenal," 30 *Aerospace America* 16, No. 5 (May 1992).

34. R.L. Sackheim, "Recent Advances in Rocket Propulsion Technology," 12 *Quest* 53, No. 2 (Winter 1989/1990). See A. Hanley, "Aerojet," 32 *Aerospace America* 9, No. 6 (June 1992).

35. B.E. Goldberg and D.R. Wiley, "Hybrids: Best of Both Worlds," 29 *Aerospace America* 29, No. 6 (June 1991).

36. *Ibid.*

37. Letter from William E. Haynes, aerospace systems analyst, to Senator Howell Heflin, 20 February 1992. See also Moteff, *supra*, note 8, at CRS-14-CRS 16.

38. K. Fisherkeller, "Solid Rockets," 29 *Aerospace America* 48, No. 12 (Dec. 1991).

39. Bennett, Hinshaw, and Barnes, *supra*, note 10, at 1. S. Aftergood, *supra*, note 16, at 35.

40. M.J. Prather, et al., *supra*, note 12 at 18, 589. W.R. Cofer III, G.L. Pellett, D.I. Sebacher, and N.T. Wakelyn, "Surface Chloride Salt Formation on Space Shuttle Exhaust Alumina," 89 *J. Geophys. Res.* (D2), 2535 (1984).

41. *Ibid.*

42. *Ibid.*

43. R. Turco, "Upper-Atmosphere Aerosols: Properties and Natural Cycles," in M.J. Prather, et al., *The Atmospheric Effects of Stratospheric Aircraft: A First Program Report*, NASA Ref. Publication 1272, 76 (January 1992).

44. *Supra*, note 1 at 14-15.

45. *Id.* at 18-19.

46. Aftergood, *supra*, note 16, at 35.

47. *Ibid.*

48. *Supra*, note 1 at 41.

49. *Id.*

50. Moteff, *supra*, note 8, at CRS-16.

51. *Id.* at CRS-16. Additionally, the following questions have

been asked: "What increase in stratospheric alumina debris can we expect from future aerospace fleets, including rockets and aircraft? What is the reactivity of alumina particles coated with sulphates? Can the total surface area of alumina particles in the stratosphere be determined? Is it significant? Are these particles an important sink for sulfate, chloride, or other stratospheric materials?" R. Turco, *supra*, note 43, at 81.

52. U.N. General Assembly Resolution 44/228, U.N. GAOR, 45th Sess., Annex 1, Supp. 228 (1989).

53. See, E.A. Parson, *Protecting the Ozone Layer: The Evolution and Impact of International Institutions* (1992).

54. These deal with the protection of the biosphere, the sustainable use of natural resources, the reduction and disposal of wastes, the wise use of energy, the reduction of risk to environmental health and safety, the marketing of safe products and services, compensation for damages, and disclosure of environmental harms posing health and safety hazards.

55. C.Q. Christol, *supra*, note 2 of *J. Space L.*, at 27.