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Some Design Considerations, Large Expulsion Bladders for Nitrogen Tetroxide and Hydrazine

A. J. Bauman

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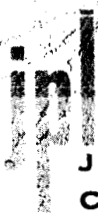
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**ABSTRACT**

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The problems of chemical compatibility, permeation and folding of bladders are discussed in the context of the requirements of the Advanced Liquid Propulsion Systems (ALPS). An extensive review of the literature on subjects pertinent to these problems is summarized. Several experiments are described in which bladder materials were permeated by the fuel and oxidizer, and the meaning of the results discussed. Folded paper models illustrating some attempts to find a scheme for collapsing bladders in a controlled manner are shown; none were found suitable for the ALPS application. Three appendixes review the status of knowledge concerning oxidization resistance and permeation of polymers and the nature of Teflon. A lengthy bibliography and list of references are included.

*Author***I. INTRODUCTION**

This Report is a general discussion of certain ideas and problems involved in the design of large expulsion bladders for long-term use with nitrogen tetroxide and hydrazine. This Report is meant to serve as a basis for discussion, because the problem is not yet solved, and to provide a bibliography for future work. The point of view is generally that of an eclectic-minded materials engineer. Appendixes on polymer systems, permeation and Teflon, with associated bibliographies are included.

**II. THE ALPS BLADDER PROBLEM**

The ALPS<sup>1</sup> concept, (Ref. 1 and 2), includes propellant storage in two large hemispherical bladders placed back to back within a common pressure envelope. The bags are to be filled with N<sub>2</sub>O<sub>4</sub> and hydrazine respectively and made to expel their contents into the combustion chamber by means of external pressure applied by gases generated in a separate catalytic reactor. The bags should withstand exposure to the fuel and oxidizer for a year at 20 to 50°C without degrading or causing the propellant to degrade. They should stand cycling without failure through at least ten expulsion/filling cycles of at least 99% expulsion efficiency. By implication, the bag material should be very thin, yet impermeable to the fuel and oxidizer.

<sup>1</sup>Advanced Liquid Propulsion System.

### III. $N_2O_4$ COMPATIBILITY

The basic design problem is that of the oxidizer  $N_2O_4$  which destroys or weakens materials other than aluminum and the noble metals which come in contact with it (Ref. 3). Hydrazine is "compatible" with many polymer systems and is not a great problem in this sense. Propellant grade  $N_2O_4$  often contains small amounts of water and nitrosyl chloride (Ref. 4) so that it is in effect *aqua regia* dispersed in anhydrous  $N_2O_4$ . These traces are probably effective in loosening noble metals plated on materials, e.g., Teflon, in contact with it. "Compatible" polymers such as the fluorocarbons are all swelled and softened by contact with the oxidizer (Ref. 5 and 6) and no elastomers known are useful in it other than as mechanically confined parts such as O-rings (Ref. 7 and 8). Silastic LS-53, for example, swells about 300 vol. % in  $N_2O_4$ . A recent report (Ref. 9) indicates that a cross-linked nitroso rubber does not swell much, but it would still make a very  $NO_2$  permeable membrane.

These facts mean that we must design collapsible thin-walled rigid bags, not elastomeric bladders. There are theoretical reasons for thinking that no elastomer will ever be chemically suitable for use as an "impermeable"  $N_2O_4$  bladder. This point will be discussed in the Appendix on polymers and  $N_2O_4$  compatibility.

Now consider Fig. 1 which shows the appearance of an 18-in.-D Teflon-TFE test bladder which has been folded by external gas pressure. The fold pattern is made up of random three-cornered folds which tend to repeat themselves when the bladder is cycled. Such folds are regions of extreme shear stress and are therefore likely sites of failure. The particular bladder shown held only water throughout its test cycle but had it been filled with  $N_2O_4$  its tensile strength would have been lowered by about 40% and its walls would have been swelled about 5 vol. % (Ref. 7). The permeability of a polymer membrane which is swelled by a permeant (gaseous or liquid) is often many orders of magnitude higher than that of one not solvated by permeant (Ref. 10). The bladder would have become very permeable to  $N_2O_4$ , therefore. The fact that Teflon-TFE is swelled by  $N_2O_4$  means that the polymer net is actually solvated by the  $N_2O_4$ . This swelling phenomenon may be a principal reason for the failure of metallic platings on Teflon to act as permeation barriers to  $N_2O_4$  when the Teflon side is exposed to the  $N_2O_4$ . Otherwise integral coats may be torn by the swelling of the substrate. The effect of this swelling is no doubt enhanced by the markedly anomalous coefficient of linear thermal expansion of Teflon which undergoes a 5-fold increase between 106 and 160°C and then returns again to its former value at the 171°C mark (Ref. 11).

#### IV. PROPERTIES OF FUEL AND OXIDIZER

Let us now briefly summarize some of the properties of oxidizer and fuel so that we may later discuss the subject of compatibility.

Anhydrous  $N_2O_4$  melts at  $-11.2^\circ C$  and boils at  $21.2^\circ C$ . At  $25^\circ C$  the equilibrium mixture is about 20%  $NO_2$  which exerts a pressure above the  $N_2O_4 \rightleftharpoons NO_2$  system of 1.2 atm (17.7 psia). About  $140^\circ C$  the mixture is entirely  $NO_2$  which with further rise in temperature decomposes to  $NO$  and oxygen, a process complete above  $620^\circ C$  (Ref. 12).  $NO_2$  reacts with unsaturated compounds to yield nitro alkyl nitriles and *vic*-dinitro alkanes (Ref. 13). It is a general oxidizing and nitrating agent strong enough to nitrate even paraffins. Commercial  $N_2O_4$  contains up to 0.1 wt. % of water and up to 0.08 wt. %  $Cl$  as  $NOCl$  (Ref. 4). One would imagine that polar surfaces (e.g., metals, glasses) immersed in this material would tend to adsorb a relatively concentrated surface coating of what is in effect dilute *aqua regia*. There are some indications that noble metal/Teflon laminates break down because of this phenomenon.

In theory anhydrous  $N_2O_4$  should be an excellent general solvent. One may calculate its Hildebrand solubility parameter,  $\delta_2$  to be about 12 at  $20^\circ C$  (Ref. 14). This parameter is in the range of 7-9 (cal/mol/cm<sup>3</sup>)<sup>1/2</sup> for most solvents. Hildebrand lists only a few solvents (e.g.,  $Br_2$ ,  $I_2$ ,  $SnI_4$ ,  $OsO_4$ ,  $CHBr_3$ ,  $CH_2I_2$ ) with  $\delta_2$ -values in this range. This solubility parameter is not perfectly related to the solvent power of the polar liquid and the values for ketones, alcohols, etc., are useless, as noted by Hildebrand. In general, if the  $\delta$ -values for a polymer and a solvent are the same, the solvent will be an excellent one

for the polymer. One may estimate that the  $\delta_2$  value for Teflon is 5 or 6 units. Teflon is swelled by Freon 113 with a  $\delta_2$  of 7.2 and dissolves in perfluoroisooctane with  $\delta = 6.0$ .

$N_2O_4$  has a surface tension at  $20^\circ C$  of 26.5 dynes/cm, a value closely approximate to that of most organic solvents. At  $25^\circ C$  the material has a density of 1.4310 gm/cm<sup>3</sup>. The gas-phase  $NO_2$  molecule is triangular in shape with a bond length of 1.20 Å and a bond angle of  $130.4^\circ$  (Ref. 12).

Hydrazine is an associated ionizing liquid which melts at  $2^\circ C$  and boils at  $113.5^\circ C$  (Ref. 15). It is miscible in water, which it physically resembles, in all proportions and its surface tension is 66.7 dynes/cm at  $25^\circ C$ . Aqueous solutions of hydrazine are quite unstable in the presence of catalytic metals such as silver, lead, copper in particular, molybdenum, or iron. Aqueous solutions of hydrazine are corrosive to aluminum alloys which otherwise are unharmed by the anhydrous base (Ref. 16). The methylhydrazines (e.g., MMH and UDHM) are reported to be more stable than hydrazine and compatible with many more materials, though they too are quite corrosive when wet. Anhydrous hydrazine is a good solvent for many inorganic salts, particularly the halides and nitrates. It has frequently been used as a plasticizer for rubber goods. Its Hildebrand solubility parameter is about 12, like that of  $N_2O_4$ . The substance is both a reducing and oxidizing agent, depending on circumstances. It is compatible with a number of elastomers (Ref. 17) provided that common inorganic compounds such as zinc or cupric oxides are not used as fillers. Such metallic oxides induce autocatalytic decomposition of hydrazine (Ref. 15).



## V. THE STANFORD-VANGO EXPERIMENT

With these properties of fuel and oxidizer in mind let us now consider the experiment of Stanford and Vango (Ref. 18), also with reference to the appearance of Fig. 1. Stanford and Vango interposed a Teflon membrane between the liquids  $N_2O_4$  and  $N_2H_4$  and found that it was quickly destroyed by a progressive blistering action within the membrane. A similar action was seen when  $NO_2$  gas alone opposed a membrane in contact with  $N_2H_4$  on one side. We carried out a number of such experiments and observed that blisters formed only on the  $NO_2$  side of the membrane and worked their way through to the  $N_2H_4$  side. Photomicrography of cross-sections of attacked Teflon film, Fig. 2, showed that the membrane failed at its edges where clamped. Evidently shear stress was greatest at that site and the swollen membrane tore mechanically. Evidently the Teflon-skived tape has a complex porous structure which readily imbibes  $N_2O_4$  me-

chanically then weakens as the individual polymer particles sorb  $N_2O_4$  molecularly. It is of some interest to note that published engineering data supports the idea that  $N_2O_4$  is imbibed first within the pores of such "cast films," swelling the material in rough approximation to the pore volume. The  $N_2O_4$ -wet membrane likely has a diffusion "constant" which is a function of its degree of solvent saturation. The phenomenon is best described in terms of the structure of Teflon cast dispersion which is discussed in Appendix C, on Teflon. The work of Crank and of Roughton appears to be pertinent to this phenomenon (Ref. 19 and 20).

Now consider the ALPS original design where a pair of hypergolic liquids are enclosed in collapsible thin-walled bags within a common pressure vessel. System failure is implicit in the paper-thin walls of the bags whose walls must be very thin if they are to have good expulsion properties. The Stanford-Vango experiment suggests that if the bladders were to be made of Teflon, blistering would result followed by sure system failure. Because all polymeric membranes are permeable to all liquids and gases to some extent, this conclusion applies to all polymer membranes. We will justify this conclusion further in the appendixes on compatibility and permeability (Appendixes A and B).

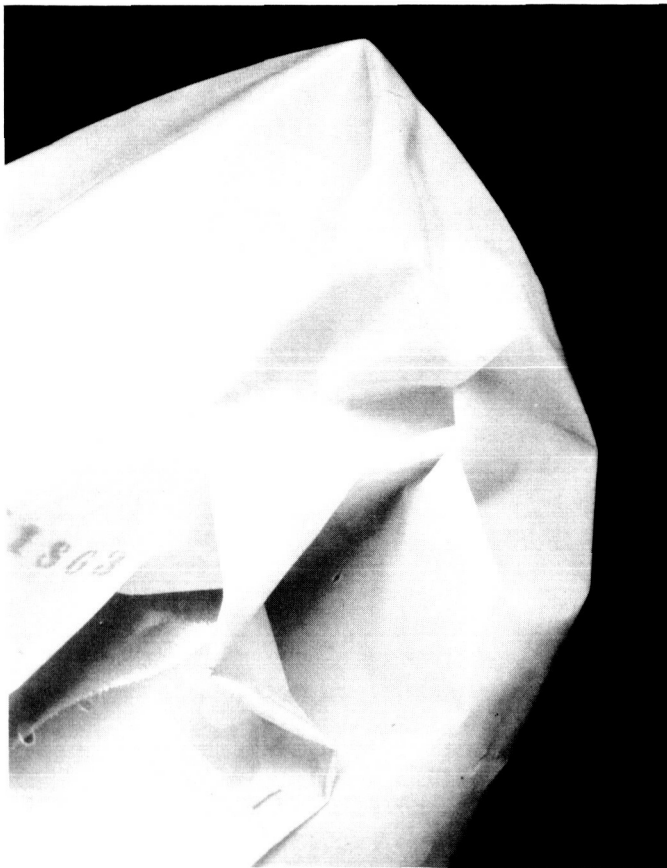


Fig. 1. Prototype ALPS bladder deformed by external gas pressure

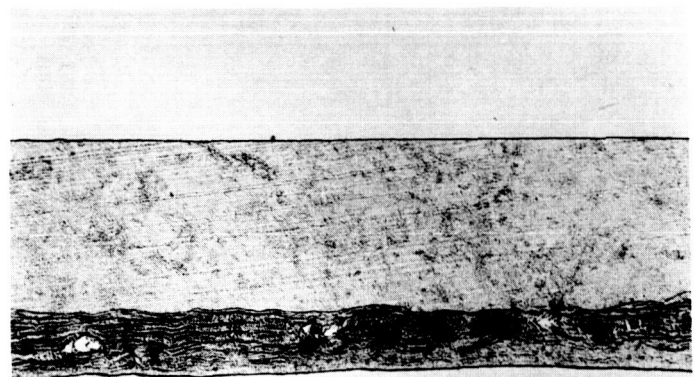


Fig. 2. Photomicrograph (300 $\times$ ) of Teflon-TFE cast film which has been sectioned normal to the axis of  $N_2O_4$  penetration into  $N_2H_4$

## VI. CRITICAL HYPERGOLICITY LIMITS

A problem basic to the ALPS expulsion bladder program is that of the prediction of miscibility limits for hydrazine and  $N_2O_4$  vapors below which spontaneous ignition will not occur. These limits have been defined for a situation in which a slug of  $N_2O_4$  is quickly injected into a volume of hydrazine vapor (Ref. 21 and 22). If "enough" oxidizer is present, "instantaneous" ignition of the vapor mixture occurs. However, no studies appear to have been made on the situation where very slow mixing of dilute  $N_2O_4$  and hydrazine vapors occurs. Such a condition might be met with if  $N_2O_4$  vapor were to leak very slowly through a faulty valve or porous membrane into a space which held  $N_2H_4$  vapor. As has been seen, the condition where  $N_2O_4$  vapor diffuses through polymeric bladder walls into an  $N_2H_4$  vapor-filled space does not occur in fact in the ALPS design. The Stanford-Vango experiments have shown that  $NO_2$  vapor or condensed  $N_2O_4$  liquid reacts within the (probably) hydrazine-wet membrane. No vapor/vapor contact appears to occur and the membrane is destroyed by the progressively-moving gas blisters described.

In the work done at the Bureau of Mines the interaction of  $N_2O_4$  and  $N_2H_4$  vapors below the spontaneous ignition values results in formation of "white solids." It seems likely that this material is a mixture of various nitrates of ammonia and hydrazine (Ref. 23). There seems no reason why such a mixing process should not proceed indefinitely, provided that the "white solids" do not themselves spontaneously ignite or explode. As long as the spontaneous ignition concentration is not met with or exceeded one would expect a slow leak of  $NO_2$  into  $N_2H_4$  to produce "white solids." The Bureau of Mines Reports also noted the formation of liquids and gases such as water,  $N_2O$ ,  $N_2$  and ammonia.

If the fuel-oxidizer mixture were saturated with inert gas at high pressure this would probably influence the spontaneous ignition levels. Furno (Ref. 24), et al., have noted that the addition of hydrocarbons to hydrazine vapor inhibits its flame propagation rate. It is possible that further work in this direction may suggest some way to raise the spontaneous ignition values of  $NO_2$  and hydrazine. Perlee, et al., have observed that vapor/vapor hypergolicity occurs between  $NO_2$  and  $N_2H_4$  (Ref. 22). But at  $25^\circ C$  in air there must be at least 9 vol % (or 2 mole %) of  $N_2H_4$  present before spontaneous ignition occurs. The  $NO_2 \rightleftharpoons N_2H_4$  reaction has been studied extensively and

inconclusively by Skinner, et al. (Ref. 25), whose spontaneous explosion data agreed qualitatively with those of Perlee. They noted that the reaction mechanism is extremely complex and is of the thermal type rather than of the chain branch explosive type. Under dilute conditions in argon below 2 mole % of each reactant, a pre-ignition reaction was observed which yielded principally ammonium nitrate and nitrous oxide. At 3 mole % of each reactant and above, the major gaseous products were nitrogen and nitric oxide with small amounts of nitrogen oxide and ammonia. At 5 mole % and above, spontaneous ignition occurred. Skinner also noted the presence of free hydrogen in the gaseous products. Hydrogen increased from 0.022 mole % for the 2 mole % reactant level to 0.91 mole % at the 4.0% reactant level. Skinner also found that high concentrations of several hydrocarbons inhibited the  $NO_2/N_2H_4$  vapor reaction rate very slightly. Perhaps some sort of chemical means might be found which would suppress this reaction.

Considering these studies in the ALPS operational design context it is not clear what effect long term "sub-critical" leakage might have. One would assume that so long as the  $NO_2$  and  $N_2H_4$  concentration remained below 2 vol % only a slow accretion of ammonium nitrate or "white solids" in the ullage would take place. Perhaps the small amount of nascent elemental hydrogen formed would ultimately cause embrittlement of thin metal membranes or of structural elements. Yet Perlee's experimental conditions are not those to be met with in the ALPS design situation. The Stanford-Vango experiments showed that, for the case of polymeric bags, damage must be expected at a level much below that of vapor/vapor hypergolicity. It may be concluded that the Bureau of Mines work will be found pertinent to ALPS only in a clearly specified engineering situation. But it is not otherwise of much value in making general predictions.

Before it is concluded that the Stanford-Vango findings absolutely interdict the use of simple polymeric membranes for ALPS bladders, consider the general means of reducing permeation through polymer films. This will be discussed at some length in the appendix but, briefly: the polymer can be made crystalline, fillers can be added, or the polymer can be cross-linked. An attractive idea is that of adding flat impermeable filler particles in sufficient amount to retain overall mechanical flexibility yet to block permeation (Ref. 26).

## VII. LEAFING PIGMENTS AND FILLED MEMBRANES

Aluminum paint owes its value as a corrosion-resistant film to the presence in the film of fine aluminum flakes oriented roughly parallel to each other. The parallel orientation of the flake is called "leafing" and it is made to take place by treating metal powders with a stearic acid solution in the process of their manufacture into flakes. The pigments fail to leaf at temperatures in excess of 150°F, the melting point of aluminum stearate. It may safely be assumed that "leafing" is a phenomenon related to the flotation behavior of surfactant-treated minerals (Ref. 27). The stearic acid chains adlineate as a monolayer and thus present a non-wettable  $\text{CH}_3$  surface to the dispersing medium, or "vehicle." Depending on many little-understood conditions, the aluminum flakes "float" to the surface of the freshly painted film where they orient roughly parallel to each other like shingles on a roof. Paint films made with such leafing pigment are good water vapor barriers.

If Teflon films could be filled with "leafing" aluminum, it would be expected that their permeation behavior would be somewhat reduced (in the absence of swelling). Some pigment was made<sup>2</sup> which was coated with perfluorooctanoic acid, but it failed to leaf in the lowest-melting perfluoro-carbon polymer available, Vydax. Zisman (Ref. 28) has noted that the lowest-energy surface possible is that made up of ordered  $\text{CF}_3$  groups (13 dynes/cm) and it was reasoned that perfluorooctanoic acid might adlineate well enough to give such a surface not easily wet by Teflon melt. In view of the high melting

temperature (250–300°C) and melt viscosity ( $10^8$ – $10^{14}$  poise) (Ref. 29) of currently available fluorocarbon polymers, it does not now seem that this rationale was at all realistic.

On the basis of surface similarity to the polymer, fluorophlogopite water-ground mica was tested, as was a form of alumina which has been reported to form an "electrostatic bond" with Teflon (Ref. 30). However, on the basis of paint technology reports and a few others, it is not likely that one would reduce gas permeation of polymer membranes by more than 30% at most by the introduction of leafing pigments into their structure (Ref. 26). In view of the  $\text{N}_2\text{O}_4$ -swelling of Teflon, this estimate for Teflon is probably optimistic.

We may fairly conclude that polymeric membranes alone are not suitable for ALPS program requirements, at least not for the design originally proposed. If an absolute permeation barrier were to be interposed between the bladders so that each would now occupy its own pressure vessel, these conclusions would not apply. Clearly, under a changed design like this the "Stanford-Vango" effect cannot occur and the possibility of vapor/vapor hypergolicity is prevented. Continuing with the original design in mind, however, the ALPS requirements apparently dictate a collapsible stiff-walled "bag" of some sort. If the bag leaks slowly or tears slightly, published work alone does not permit a failure prediction. Two ideas pertain to the problem: how shall we minimize the number of folds (stress points) in the bag and how shall we keep the concentration of vapors in the free system below hypergolic levels? The latter point will be considered first.

<sup>2</sup>Very kindly provided by Mr. D. R. French of Metals Disintegrating Company, Elizabeth, N. J.

## VIII. REMOVAL SYSTEMS

In a sense, chemical removal systems for preventing the  $\text{NO}_2$  permeation of Teflon have already been tried. Schuerch and Wituki (Ref. 31) made a quilted sandwich structure of Teflon film which enclosed  $\text{NO}_2$  absorbents such as powdered charcoal. The test "membranes" were unhandily thick and the design did not eliminate the possibility of the  $\text{N}_2\text{O}_4$  eventually saturating the "sandwich packing," even if it did not react (probably) explosively (Ref. 32 and 33) with it.

An efficient  $\text{NO}_2$  removal system would permit one to use thin (useful) membranes for ALPS bladders by keeping  $\text{NO}_2$  levels below even the "Stanford-Vango effect" level. If it were feasible to allow the damage to the Teflon, the hydrazine-backed Teflon membrane of the fuel bag would be a superb  $\text{NO}_2$ -removal system. If one wanted to use such permeable material it would be necessary to consider the competition between the removal system and the "Stanford-Vango effect." Let us suggest a few ideas for the design of  $\text{NO}_2$ -removal systems as a basis for discussion:

1. Magnetically cooled trapping ( $\text{N}_2\text{O}_4$  melts at  $-11.2^\circ\text{C}$ ) would physically remove the gas.
2. Chemical gas-washing, e.g., by strong alkali solution such as KOH, would remove  $\text{NO}_2$ . A glass trap containing concentrated aqueous KOH would be sparged by the recirculated gas stream which would vent through a microporous Teflon water barrier.
3. Catalytic conversion of  $\text{NO}_2$  or  $\text{N}_2\text{H}_4$  to light gases. Wikstrom and Nobe convert  $\text{NO}_2$  to  $\text{N}_2$  and  $\text{O}_2$  by means of an alumina/cupric oxide catalyst (Ref. 34). The light gases formed could either be vented through the system's hull or tied up chemically as perhaps CuO or calcium cyanamide.

Filled membranes such as aluminum-filled Teflon have greatly improved tear resistance but are still quite  $\text{NO}_2$  permeable. Evidently some composite metal-polymer or tear-resistant metal membrane is needed to satisfy the original ALPS design requirements. Only metals have nearly zero permeability to gases and liquids but thin metal foils tear easily. Let us consider a few methods of making flexible, impermeable membranes.

1. Aluminum sheet is treated by the Cahne method (Ref. 35) which leaves its surface etched with narrow-necked pores. Teflon dispersion sintered on such a surface is rooted mechanically in the pores

and is not affected by immersion in  $\text{N}_2\text{O}_4$ . However, the Cahne process is not applicable at present to membranes less than about 1 mil thick. Such Teflon/aluminum membrane at present is thick and inflexible. Other reported Teflon coating methods (Ref. 36-38) do not produce coatings which resist  $\text{N}_2\text{O}_4$ .

2. Etched Teflon is plated by various processes then treated to yield a lead or lead-indium composite (Ref. 39 and 40). The product is completely impermeable to anhydrous  $\text{N}_2\text{O}_4$  liquid in a very long term static test. However, the stiff and rather thick material poses a difficult fabrication problem for bladder applications. The effects of long term exposure particularly of indium to commercial (wet)  $\text{N}_2\text{O}_4$  have yet to be studied. If these objections can be overcome the "Vango-Krasinsky" process may eventually produce a suitable  $\text{N}_2\text{O}_4$  bladder material. One could easily use a butyl-rubber bladder for the  $\text{N}_2\text{H}_4$  which would otherwise be adversely affected by the catalytic effect of the lead.
3. Schonhorn's "molecular adhesive" process (Ref. 41) has been used successfully to fabricate strong aluminum/polyethylene bonds. Because extremely thin aluminum and polyethylene may be bonded by this means it may be of value to attempt the fabrication of multi-walled structures of this type. A structure made up of very many thin membranes should have excellent tear resistance (Ref. 42 and 43). Polyethylene is completely destroyed by long-term exposure to  $\text{N}_2\text{O}_4$ , but this would only occur at pinhole sites in the aluminum. With very many very-thin metal membranes the probability of overall failure would be reduced, particularly with the polyethylene used as "bulking" between them (Ref. 42).
4. It is feasible to make thin flexible metal textiles (Ref. 44) such as those used for reentry drogues. Such textiles are currently in production. It should be feasible to use such a textile as a support for thin metal, e.g., stainless steel or aluminum, membranes by contact welding the two together by means of electron-beam welding.
5. It may be possible to fabricate a thin self-sealing membrane of a rather complex design. For example, consider the space between two thin aluminum membranes to be filled with tiny, highly magnetized

metal microspheres (alnico) mixed with a proper number of gelatin microcapsules which contain a special liquid metal alloy. The magnetic microspheres would, in a sense, constitute a thixotropic binder for the gelatin microspheres. The membrane could easily be deformed and, if quilted properly, would return to its former configuration. If  $N_2O_4$  were to enter it at a pinhole, it would quickly attack the gelatin microcapsules and release their contents. The liquid alloy would wet the alnico microsphere "binder," thus sealing off the penetration. A bionic example of such a phenomenon is that of blood clotting round a puncture wound. Rather than magnetic powder, very fine silver wire could be used. This would amalgamate with an encapsulated liquid, e.g., mercury-thallium alloy.

6. The liquid leakage problem may be avoided by devising some sort of slurry monopropellant. Both  $N_2O_4$  and  $N_2H_4$  have been gelled by the addition of large amounts (8-12%) of colloidal silica and it may be possible to encapsulate  $N_2H_4$  and disperse

it in gelled  $N_2O_4$ . Unfortunately, impulse would be reduced and disaster ever imminent.

Prins and Hermans have shown that gas flux through the pinholes of metal-polymer laminates is proportional to the perimeter of the holes, rather than to their total area (Ref. 45). Evidently any sort of metal membrane design must take this into account and production quality control must emphasize membrane integrity.

In summary, thus far the ALPS design problem may be broken down for study into three operational areas.

- a. The interaction of the bladder material and the fuel or oxidizer.
- b. The vapor/vapor interaction of fuel and oxidizer within the bladder membrane or outside of it.
- c. The mechanical folding design of the bladder structure so as to minimize the number of folds and thus the probability of system failure.

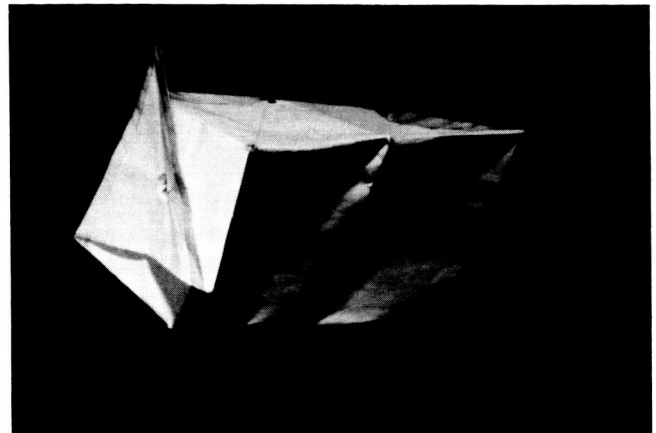
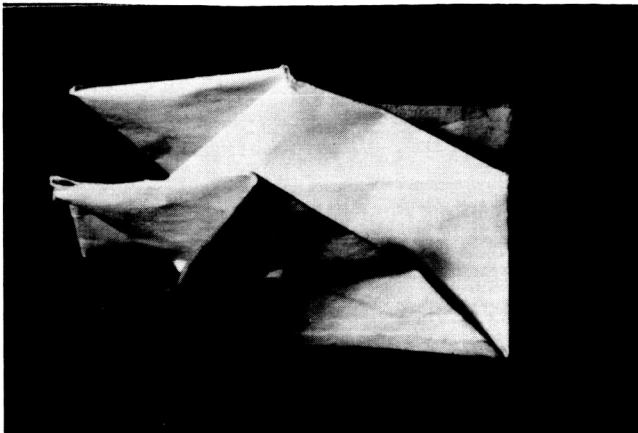
## IX. BAG FOLDING

The design of flat-folding thin-walled structures so as to minimize the number of folds is somewhat outside the scope of this discussion. However, it is a key element of the overall design problem and merits at least some cursory attention here. The subject has been reviewed by Forbes (Ref. 46) and recently from the ALPS viewpoint by Porter and Stanford (Ref. 18). The problem does not seem to be a popular one with mathematicians. Michael Goldberg<sup>3</sup> has considered the general case of a flat-folding closed surface and noted that as the volume efficiency increases to 100% this requires the number of folds to increase exponentially towards infinity. His

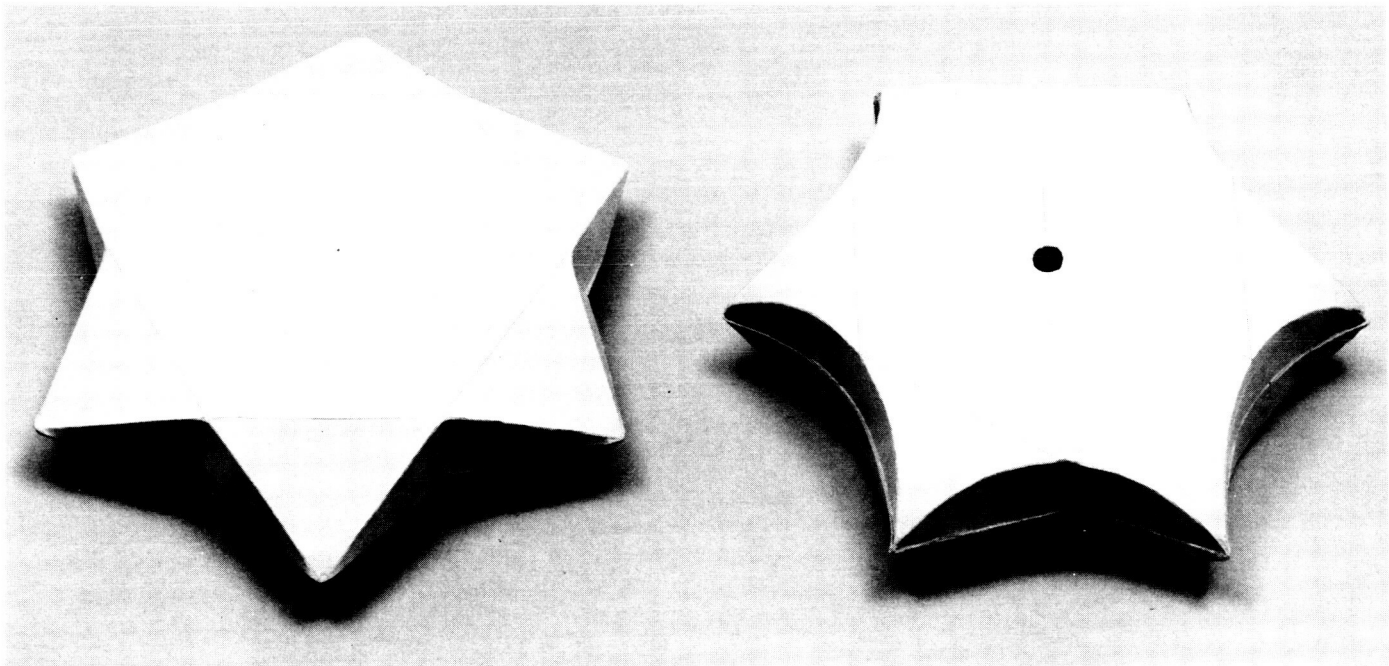
designs (Fig. 3) resemble the familiar Japanese lantern. The straight-sided model buckles inward at 48 folds while the curved-sided model does this at 18 folds. Goldberg feels that stiff-walled manifolds like this probably can be made to collapse with not much more than 90% volume efficiency. Arthur H. Stone<sup>4</sup> has very kindly provided the "screw prism" design shown in Fig. 4 which folds to collapse with 9 folds per segment. Possibly such a design might be used in some sort of ganged array. The problem of designing of such structure merits more attention. Numerous empirical examples of "solutions" to the problem exist in the patent literature; U.S. Patent 2,815,883 is typical (Ref. 47).

<sup>3</sup>Personal communication.

<sup>4</sup>Personal communication.



**Fig. 3. "Goldberg's morningstars" idealized flat-folding structures with minimal fold numbers**



**Fig. 4. "Stone's screw-prism" partially flattened and expanded views of a flat-folding structure with only 9 folds per segment**

## X. AN ADVANTAGEOUS DESIGN MODIFICATION

Vango<sup>5</sup> has pointed out that a porous  $N_2O_4$ -filled bag at zero g would, in a short time, become coated with a film of liquid  $N_2O_4$ : in effect there would be a large drop of  $N_2O_4$  liquid which incidentally would include some membrane. The process would stop at this stage. In a gravitational field, of course, the liquid would leak out till the hydrostatic pressure in the bladder equalled that in the surrounding pressure vessel. This suggests that an improved ALPS design would include a permeation barrier between the two bladders.

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<sup>5</sup>Personal communication.

## XI. CONCLUSIONS

If the original ALPS design is to be kept, no polymeric membrane alone will be satisfactory. Only tear-resistant completely integral metal composite membranes will be satisfactory. The design should include a system, chemical or physical, to remove  $NO_2$  from the ullage. If the original ALPS system is modified to include a permeation barrier between the fuel and oxidizer bladders, all danger of vapor/vapor hypergolicity will be removed. At zero g only a small  $N_2O_4$  loss from the expulsion bladder would occur with the modified design and polymer membranes alone could be used. A number of designs of impermeable flexible membranes are suggested.

## APPENDIX A

### The Chemical Stability of High Polymers Toward Oxidizing Agents

Much of the literature on the oxidative degradation of polymers is summarized in Ref. 48 and 49 but very little is known of the process, relative to that of thermal degradation. One may make the general statement that at a given temperature the oxidative degradation of any material is always rapid compared with that of pure thermal degradation.

In the context of the general phenomenon of polymeric thermal degradation it may be mentioned that decomposition characteristics are the result of a competition between a "zip" (depolymerization) process and a transfer process. Simha (Ref. 50) has pointed out that oxygen acts as an additional source of free radicals by initiation and transfer and hence decreases the importance of the "zip" step. Other gases may produce catalysis or inhibition but generally, active atmospheres or solvents will randomize the chain process if it was not so to begin with.

The oxidation of complex molecules such as polymers is a very involved process but there is evidence that many of the direct oxidation reactions of small molecules also occur in reactions of polymers (Ref. 51). Hence, the discussion which follows applies at least in part to some of the features of monomer thermal degradation.

Although oxidative degradation occurs with either unsaturated or saturated polymers (or monomers) it is much more important in those that are unsaturated. The oxidation of an unsaturated molecule usually involves two phases—the peroxidation of the molecules followed by subsequent decomposition of the peroxides to give a multitude of decomposition products (Ref. 52). Often the overall rate depends upon the stability of the peroxides formed. The formation of the hydroperoxide groups is a chain reaction which leaves the unsaturation of the molecule unimpaired as long as no secondary decomposition reactions of the hydroperoxide groups take place. The double bond activates the methylene group in the  $\beta$  position and this group then serves as a point of attack for the oxidation. Groups such as methyl groups make adjacent methylene groups still more reactive. The methyl end groups also may be activated by adjacent aromatic substituents, in which case oxidation occurs at the tertiary carbons. Systems that are conjugated differ in that they do not usually form hydroperoxides even with methylene

groups in favorable positions. Instead, the trend is for the addition of oxygen at the ends of a diene segment, resulting in an oxygen bridge to give either transannular or polymeric peroxides. The hydroperoxides formed first in oxidizing systems decompose appreciably early in the reaction and the products may be still further oxidized. The overall products may then be enormously complex. The absorption of oxygen by unsaturated compounds generally is autocatalytic and it is usually accelerated by heavy metal impurities, such as iron or copper.

The oxidation of unsaturated polymers is accompanied by a deterioration of the mechanical properties of the polymer. For example, it usually becomes brittle as a consequence of the rapid increase in molecular weight. This shows that chain scission and crosslinking reactions either accompany or are a part of the oxidation process. It is believed that the reactions are brought about by oxidation of the double bond, followed by chain scission. Crosslinking is probably a consequence of the scission.

Saturated polymers are much less reactive toward oxidation than the unsaturated ones and their physical properties do not break down so markedly. Aromatic substituents have a strong activating effect on the  $\beta$  methylene groups, as in unsaturated systems, and peroxidation occurs at this point.

Hinshelwood (Ref. 48) has summarized the effects of the structure of saturated hydrocarbons on their oxidizability by considering the maximum rates attained by many compounds under similar conditions. His conclusions are as follows:

1. The rate of oxidation is greatly decreased by the introduction of extra methyl groups into a hydrocarbon. The mode of initial attack by oxygen which leads to the peroxide most effective in chain branching (auto-oxidation) is that made on a methylene group as remote as possible from methyl.
2. If there is no place to attack except a methyl group, there is a greatly reduced oxidation rate relative to that of a corresponding compound with a methylene group.
3. The substitution of chlorine increases the rate and acts by destroying the symmetry of any methyl



group into which the substituent enters, and by a direct inductive effect of the chlorine atom.

4. Carbonyl groups and amino groups increase oxidizability.
5. Ethers oxidize faster than paraffins.
6. For unsubstituted hydrocarbons, chloro compounds, amino compounds, and ketones, the rate increases greatly as the chain is lengthened. But with ethers,

the increase from ethyl ether to higher ethers is relatively small.

Overall, the rate of oxidation usually depends on the stability of the hydroperoxide formed. Electron-attracting substituents (e.g., carbonyl, halogen) increase the rate while the opposite is true for electron-repelling substituents such as methyl. In this context it is interesting that several halocarbons have recently been reported to explode in contact with  $N_2O_4$  (Ref. 32 and 33).

## I. SUMMARY

An ideal polymer system for use with  $N_2O_4$  should be saturated and should have pendant methyl groups along the chain. It should contain no aromatic systems or other unsaturation nor any halogen other than fluorine.

## II. THE FLUOROPOLYMERS

Systems which have exactly this design are the fluorocarbons, such as Teflon, which are marketed under many names: Table A-1 lists some typical chemical structures and Table A-2 lists some typical physical properties. These compounds can be liquids, greases, thermoplastics or elastomers. Although pure hydrocarbon polymers such as polyethylene are structured in agreement with our model, they do not promise long-time compatibility with  $N_2O_4$ . Some branched polyethylenes are reported to have excellent short time  $N_2O_4$  compatibility (Ref. 49), but only the fluorocarbons look good for long-term compati-

bility. Table A-3 lists some compatibility properties of typical fluoropolymer systems with various chemical solvents.

Polytetrafluoroethylene (Teflon) and polychlorotrifluoroethylene (Kel-F) were the first fluoropolymers exploited commercially and Teflon is to be given a separate section later in this report series because of its importance.

The next advance was the development of the fluoroelastomers (Silastics) to replace silicone rubbers in ap-

Table A-1. Chemical structures and trade names of fluoropolymers

Name	Mer	Trade name	Type
Polytetrafluoroethylene (TFE)	$-(CF_2CF_2)_n-$	Teflon, <sup>a</sup> Fluon <sup>b</sup> Fluon GP 1 <sup>b</sup> Algoflon D 60 <sup>c</sup> Soreflon D 119 <sup>d</sup> Fluoroplast-4 <sup>e</sup>	Thermoplastic
Polychlorotrifluoroethylene	$-(CF_2CFCl)_n-$	Kel-F, <sup>f</sup> Fluorothene <sup>g</sup> Polyfluoron Hostafflon <sup>h</sup> Genetron <sup>i</sup> Plastic HL <sup>i</sup> Halon <sup>i</sup>	Thermoplastic
Polyvinylidene fluoride	$-(CH_2CF_2)_n-$	RC-2525, <sup>j</sup> Kynar <sup>j</sup>	Thermoplastic
Polyvinyl fluoride	$-(CH_2CHF)_n-$	Teslar, <sup>b</sup> Tedlar <sup>a</sup>	Thermoplastic
Tetrafluoroethylene-hexafluoropropylene copolymer	$-(CF_2CF_2CF_2CF \cdot CF_3)_n-$	Teflon 100-X <sup>a</sup> Teflon FEP <sup>a</sup>	
Vinylidene fluoride-chlorotrifluoroethylene copolymer	$-(CH_2CF_2CF_2CFCl)_n-$	Kel-F Elastomer <sup>k</sup> Kel-F 500, <sup>k</sup> Kel-F 800 <sup>k</sup> Kel-F 820, <sup>k</sup> Kel-F 3700 <sup>k</sup> Kel-F 5500 <sup>k</sup>	Thermoplastic resins and elastomers
Vinylidene fluoride-hexafluoropropylene copolymer	$-(CH_2CF_2CF_2CF \cdot CF_3)_n-$	Viton A, <sup>a</sup> Viton B, <sup>a</sup> Viton A-HV, <sup>a</sup> Fluorel <sup>k</sup> Kel-F 214 elastomer <sup>l</sup> Fluorel K, <sup>k</sup> Fluorel 2141 <sup>k</sup> Fluorel KX, 2141 <sup>k</sup>	Elastomers

<sup>a</sup>E. I. du Pont de Nemours & Co., Inc.  
<sup>b</sup>Imperial Chemical Industries, Ltd. (England)  
<sup>c</sup>Montecatini (Italy)  
<sup>d</sup>Société des Résines Fluorées (France)  
<sup>e</sup>Russian  
<sup>f</sup>Acme Resin Corp.  
<sup>g</sup>Union Carbide & Carbon Corp.  
<sup>h</sup>Farbwerke Hoechst A. G. (Germany)  
<sup>i</sup>Allied Chemical & Dye Corp., General Chemical Division  
<sup>j</sup>Pennsalt Chemicals Corp.  
<sup>k</sup>Minnesota Mining & Manufacturing Co.  
<sup>l</sup>M. W. Kellogg Co.

Table A-2. Typical physical properties of fluoropolymers

Property	Teflon TFE	Teflon FEP	Kel-F	Kynar	Tedlar
Structure	$-(CF_2-CF_2)-$	$-(CF_2CF_2CF_2CF_2CF_3)-$	$(CF_2CFCl)$	$-(CH_2CF_2)-$	$-(CH_2CHF)_n-$
Appearance and color	Translucent to opaque; white to blue-gray	Translucent to trans- parent; colorless	Transparent to translucent	Transparent to translucent	Transparent
Transition point, °C	327	285-295	216	171	
Max working temp, °C	250-300	225	200	—	204
Fabrication temp, °C	350-400	382-400	250-350	204-288	—
Preferred working range, °C	-80-250	-85-200	—	-70-150	-73-106
Viscosity of melt, poise	10 <sup>22</sup>	3-10 × 10 <sup>4</sup>	10 <sup>6</sup>	—	—
Elongation at break, %	50-400	250-330	20-80	300	110-260
Tensile strength, lb/in. <sup>2</sup>	2000	2700-3100	5700	7000	9600-19000
Coefficient linear thermal expansion/°C	9.9 × 10 <sup>-5</sup> (25-100°C)	8.30-10.52 × 10 <sup>-5</sup> (-70-70°C)	7 × 10 <sup>-5</sup>	15.3 × 10 <sup>-5</sup>	5 × 10 <sup>-5</sup>
Hardness, durometer D	55-70	55	75-80	80	—
Specific gravity	2.1-2.3	2.15-2.17	2.1-2.15	1.76	1.38-1.57
Refractive index	1.36	—	1.43	1.42	1.46
Volume resistivity, Ω/cm	10 <sup>19</sup>	2 × 10 <sup>18</sup>	10 <sup>18</sup>	2 × 10 <sup>-14</sup>	10 <sup>16</sup> -10 <sup>18</sup>
Dielectric constant, 60 cps	2.0	2.2	2.65	8.4	6.8 (1 kc)

Table A-3. Resistance of typical fluoroelastomers to chemicals and solvents<sup>a</sup>

Reagent	Kel-F 214 Fluoral Viton A	Kel-F Elastomer Kel-F 800	Fluororubber 1F 4 or 2F 4 (Acrylates)	Fluoropolyester (Adipates)	Silastic LS 53 (Fluorosilicones)	TFNMTFE (Nitroso rubbers)
Fuming sulfuric acid	4.8 (7/24) <sup>b</sup>	1 (27/25) <sup>b</sup>				
Red fuming nitric acid	16 (7/24)	24 (27/25)				
Nitric acid, 90%	30 (7/24)		74 (0.13/25) <sup>b</sup>		4 (7/25) <sup>b</sup>	
N <sub>2</sub> O <sub>4</sub>	300 (7/25) <sup>c</sup>	653 (1/25) Kel-F 5500			300 <sup>d</sup> (7/25) <sup>c</sup>	174 (7/25) <sup>c</sup>
N <sub>2</sub> H <sub>4</sub>	Embrittles; flakes	Blisters; gets tacky			Dissolves	
Acetone	271 (7/24)	181 (7/24)	38-85 (14/25)		180 (7/25)	
Ethanol	1.7 (7/24)	6 (27/25)	0-10 (14/25)		5 (7/25)	
Diester oil	19.6 (7/204)	105 (3/177)	3 (7/205)	1-3 (3/177)	10 (3/170)	
Ethyl acetate	0 (100/24)		100 (14/25)			
Freon 113	11 (7/24)	180 (1/25)				
Freon 22	90 (20/24)		215 (2/25)			
Freon 12	30 (20/24)		155 (3/25)			

<sup>a</sup>Ref. 62, p. 278.  
<sup>b</sup>Typical representation, indicating volume percent change and days/temp °C.  
<sup>c</sup>Ref. 49.  
<sup>d</sup>Retains strength after near complete recovery of elasticity and size within 1 hr.

Table A-4. Miscellaneous fluoropolymers

Name	Mer	Trade name	Type
Poly-1,1-dihydroheptafluorobutyl acrylate	$-(\text{CH}-\text{CH}_2)_n-$   CO O CH <sub>2</sub> C <sub>3</sub> F <sub>7</sub>	Fluoro-rubber 1 F4 <sup>a</sup>	Elastomer
Poly-1,1-dihydro-3-trifluoromethoxybutyl acrylate	$-(\text{CH}-\text{CH}_2)_n-$   CO O CH <sub>2</sub> CF <sub>2</sub> CF <sub>2</sub> OCF <sub>3</sub>	Fluoro-rubber 2 F4 <sup>a</sup>	Elastomer
Polyfluoropentamethylene adipate	$-(\text{O CH}_2 \cdot (\text{CF}_2)_3 \text{CH}_2 \text{O CO} \cdot (\text{CH}_2)_4 \text{CO})_n-$	Fluorinated polyester <sup>b</sup> (not a trade name)	Elastomer
Methyl-3,3,3-trifluoropropyl polysilicone rubber	CH <sub>3</sub> $-(\text{CF}_3\text{CH}_2\text{CH}_2\text{Si}-\text{O}-)_n-$	Silastic LS-53 <sup>c</sup>	Elastomer
Polymonochlorotrifluoroethylene	$-(\text{CF}_2\text{CFCl})_n-$	Fluorolubes <sup>b</sup>	Oils, waxes
Trifluoronitrosomethane tetrafluoroethylene	$-(\text{NOCF}_2\text{CF}_2)_n-$   CF <sub>3</sub>	J. Montermoso, U.S. Army Quartermaster R&D Center, Natick, Mass. Not com- mercially available.	Elastomer
Perfluoroalkylamide polymers	$(\text{C}_4\text{N}_2\text{C}_2(\text{CF}_2)_x)_n$	Not commercially available.	
Phosphorous fluoronitride polymers	$-(\text{NPF}_2)_n-$	None <sup>d</sup>	

<sup>a</sup>Minnesota Mining & Manufacturing Co.  
<sup>b</sup>Hooker Electrochemical Corporation, Niagara Falls.  
<sup>c</sup>Dow Corning Corporation.  
<sup>d</sup>Xanthippe Chemical, Butte, Montana.

applications at around 200°C in contact with lubricants and hydrocarbon fuels to which the silicones have poor resistance at these temperatures.

As yet, however, no elastomer exists which is capable of long-term resistance to strong oxidizing agents or which

can stand temperatures above 400°C for very long. Many attempts are being made to find such a material and a wide spectrum of polymer systems has been studied so that particular rules relating polymer structure to chemical and thermal stability might be found. In general, the polymer systems studied thus far fall into three categories:

those with carbon-carbon backbones; those with semi-inorganic backbones; and those with inorganic backbones. In the first group are found the vinyl, the fluoro-aromatic and the perfluoroalkylamidine systems. In the second group are the semi-inorganic perfluoronitroso polymers

having NOCC or CNCN backbones, and in the last category are the silicones (Si-O-Si-O), the polysiloxanes ( $\text{RSiO}_{1-6}$ ) and the polyfluoronitrides ( $\text{NPF}_2$ ). These categories will be surveyed briefly in the order given. Table A-4 lists a few of their structures.

### III. VINYL POLYMERS WITH A CARBON BACKBONE

Many aliphatic fluoro-carbon olefins have been made, polymerized and co-polymerized and the general rule, as we have seen, is that polymer stability, both thermal and chemical, is greatest in proportion to the amount of fluorine in the system; any extraneous abstractable hydrogen present lessens this stability. The stability of perfluoro-compounds is due to the high dissociation

energy of the carbon-fluoride bond and to the shielding effect and electronegativity of the fluorine atoms. Fluorine is slightly larger than hydrogen (0.64 Å vs 0.61 Å) and the C-C bond in fluorocarbons is probably a little shorter (Ref. 53) than that in hydrocarbon systems. Thus, the fluorine atoms form a compact sheath around the carbon chain to protect it from attack.

### IV. THERMOPLASTICS

Polytetrafluoroethylene (Teflon)<sup>6</sup> the most stable vinyl fluoro-polymer has a working range which extends to 300°C. It is attacked only by molten alkali metals, and at high temperature (300°C) by the tetrachlorides of the silicon group. It is swollen slightly (1-3%) by certain polychlorotrifluoro oils (Fluorolubes) and by the polyhalogenated ethane refrigerants (Freons). It is slightly soluble in perfluorinated solvents, from which it has been crystallized. Although Teflon is technically a thermoplastic, it cannot be fabricated by conventional techniques since its melt viscosity is about  $10^{12}$  poise at 350°C, the working temperature (Ref. 54).

The copolymer of tetrafluoroethylene with hexafluoropropylene (FEP) was designed to be a low-melting elastomeric Teflon. Its melting temperature is about 290°C as compared to that of Teflon's 327°C and it can be processed by normal means.

Polychlorotrifluoroethylene (Kel-F) also has a low-melt viscosity and melting temperature due to the presence of the bulky (0.99 Å) chlorine atoms in the chain. The chlorine also makes Kel-F less stable to thermal and chemical degradation (Ref. 49) and it is swollen by some aromatic and halogenated organics. Less than a week of exposure to  $\text{N}_2\text{O}_4$  causes Kel-F to lose 60% of its initial

<sup>6</sup>See Tables A-1-4 for trade names and structures of the mers.

tensile strength and 90% of its initial flexural modulus (Ref. 55). It also has a high thermal degradation rate at fabrication temperatures.

Polyvinylidene fluoride (Kynar) is degraded by fuming sulfuric acid and dissolved by acetone, dimethyl sulfoxide and dimethyl acetamide. It loses about 10% of its tensile strength in  $N_2O_4$ , but swelling data is not available at this time. Kynar reacts with primary amines such as

*n*-butyl amine (and probably hydrazine) to form dark, brittle products. Its melting temperature ( $171^\circ C$ ) is lower than that of either Teflon or FEP but it is good indefinitely at  $150^\circ C$  and for short times at  $260^\circ C$ .

Polyvinyl fluoride (Tedlar) is an unknown quantity at this writing, but it is likely to have even poorer solvent resistance than Kynar in view of the presence of H atoms on the chain.

## V. FLUORO-ELASTOMERS

The chemical structures of the fluoro-elastomers developed thus far are summarized in Table A-4. The copolymer of vinylidene fluoride with hexafluoropropylene (Vitons, Fluorel) is available in several grades which are produced by varying the polymerization conditions and monomer ratios. The elastomeric character of these copolymers is due to the marked asymmetry produced in the chain by the pendant trifluoromethyl groups, as well as to the flexibility introduced by the methylene groups. These materials may be cross-linked at the methylene sites by means of  $\beta$ -radiation, peroxides or

polyfunctional amines. They swell as much as 300% in  $N_2O_4$  at room temperature (Ref. 49) but quickly lose the  $N_2O_4$  imbibed when removed and recover their physical properties almost completely.

The copolymer of vinylidene fluoride with chlorotrifluoroethylene (Kel-F Elastomer) is also sold in several grades based on the proportions of monomers used. Some of these such as Kel-F 5500 have good short-time resistance to  $N_2O_4$ ; incidentally, this material detonates in the presence of chlorine trifluoride (Ref. 53).

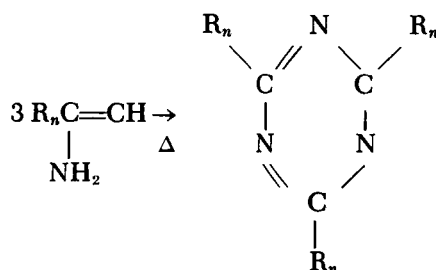
## VI. POLYFLUORO-AROMATIC SYSTEMS

Many prospective monomers based on more-or-less fluorinated aromatic systems have been prepared but no polymers based on them are commercially available. Such polymers show great promise theoretically of having

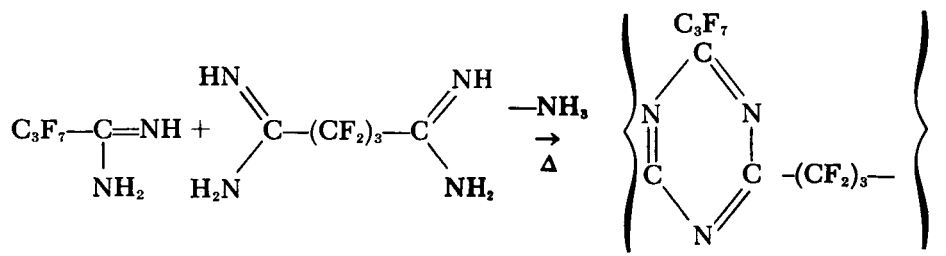
extreme thermal stability. It would be necessary to perfluorinate them, however, if they were to be even slightly compatible with  $N_2O_4$  and even then the aromatic bonds would be sites of attack, thus ruling them out.

## VII. PERFLUOROALKYLAMIDINE SYSTEMS

Perfluoroalkylamidines,  $R_nC (:NH) NH_2$ , where  $R_n = CF_3$ , etc., are prepared by the addition of ammonia to perfluoroalkyl cyanides. They trimerize when heated to yield the 1,3,5-tris-(perfluoroalkyl)-triazines (Ref. 56).

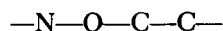


The reaction extended to diamidines yields condensation polymers which are said to have good thermal and probably good chemical stability. The pyrolysis of perfluoroglutarodiamidine or perfluoroadipodiamidine yields materials said to be resistant to strong oxidizing agents and stable in air at 350° for long periods. Condensation of these diamidines with heptafluorobutyroamidine yields elastomers, with the probable structure below (Ref. 57 and 58).

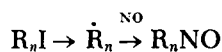


### VIII. POLYMERS WITH SEMI-ORGANIC BACKBONES OF THE -N-O-C-C- OR -C-N-C-N- TYPES

A new type of polymer system has resulted from the copolymerization of fluoroalkyl nitroso-compounds with olefins. The —N=O group acts like a —C=C— group so that the polymer repeating unit is usually

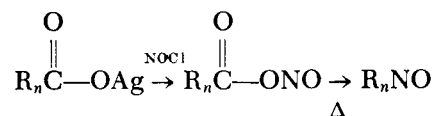


The fluoroalkyl nitroso monomers (such as trifluoro-nitrosomethane) are easily prepared by photochemical reaction of the fluoroalkyl iodide with nitric oxide (Ref. 59):

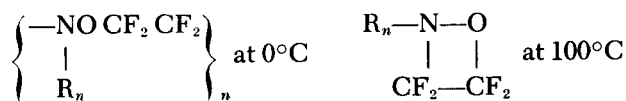


The iodine produced is taken up in mercury.

Recently (Ref. 60) an even cheaper route:



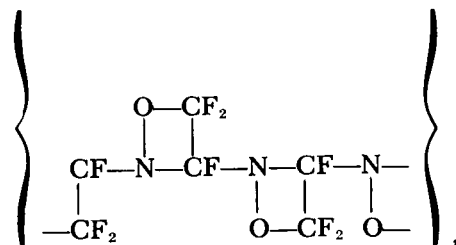
has been developed. Perfluoroalkylnitroso monomers react with olefins, such as tetrafluoroethylene, to yield a 1:1 copolymer and an oxazetidine (Ref. 61).



### IX. POLYMERS WITH INORGANIC BACKBONES CONTAINING SILICON

The polymers are either oils, waxes or elastomers depending on the olefin used and the exact conditions. Their resistance to oxidizing agents is said to be good but the trifluoronitrosomethane-tetrafluoro-ethylene compound 1:1 is quickly degraded by N<sub>2</sub>O<sub>4</sub> at room temperature (Ref. 49). This copolymer is a white, opaque elastomer stable to prolonged heating in air at 180°. Since the olefin or nitroso compound can be of any type, this reaction is quite general and such elastomers made from other perfluorinated compounds may be promising. Vango (Ref. 62) has recently noted that a proprietary cross-linked TENME elastomer has little swell in N<sub>2</sub>O<sub>4</sub>. A British Patent (789,254, January 15, 1958) was taken out by ICI, but apparently the commercial production of these materials is not attractive. Another polymer system

in this group is that formed from the homopolymerization of a nitroso-compound which is unsaturated, for example CF<sub>2</sub>:CF N:O. This compound forms a polymer via oxazetidine ring formation which has a C—N—C—N—C— structure.



The inorganic polymer systems in use at this writing are chiefly the silicones and the polysiloxanes. They have good thermal stability but poor resistance to solvents, especially at elevated temperatures. For that reason, as mentioned, the fluoro-silicon rubbers (Silastics) were developed in an effort to improve matters.

The precursors of the silicones  $(R_2SiO)_n$  and the polysiloxanes  $(RSiO_{1-6})_n$  are the halides,  $R_2SiCl_3$  and  $RSiCl_3$ , respectively. The polyfluoroalkyl silicon chlorides can be prepared from the halides by a free radical route to yield compounds with the fluorine either  $\alpha$ ,  $\beta$  or  $\gamma$  to the silicon

atom in the  $\overset{\gamma}{C}-\overset{\beta}{C}-\overset{\alpha}{C}-S_1$  system (Ref. 61). Only the compounds which have the  $\alpha$  or  $\beta$  fluorines are hydrolyzed by bases presumably by nucleophilic attack on the silicon which is activated by the attached electronegative fluoroalkyl group. Silastic LS-53 is a polymer prepared from a gamma-fluorine monomer and it has excellent thermal and chemical resistance. It swells up to 300% in  $N_2O_4$  but, like the Vitons, quickly returns to normal in every way when removed (Ref. 49). For that reason, LS-53 is widely used as an O-ring material for applications in contact with  $N_2O_4$ . The silicone rubbers disintegrate quickly in contact with hydrazine.

## X. INORGANIC POLYMERS, OTHER THAN SILICONES

For some time there has been an extremely active research effort directed towards the synthesis of inorganic polymers for high temperature applications. However, such systems exhibit, generally speaking, poor resistance to hydrolytic attack. They do not look at all promising at present for use with  $N_2O_4$ .



## APPENDIX B

### Permeation Through Membranes

Permeation of gases and liquids through membranes has been studied extensively and several excellent reviews and books have been published (Ref. 63-65). Gaseous permeation through polymeric membranes has received the major share of attention, though liquid permeation studies (e.g., water desalinization) (Ref. 66) are becoming more popular. Recent reviews cover most of the liquid permeation literature (Ref. 67 and 68). If liquid  $N_2O_4$  contacts a Teflon membrane, it quickly swells it and the "saturated" membrane likely offers little resistance to permeation. This is liquid/liquid diffusion. The situation is like that of "self diffusion" in the liquid. The liquid permeation rate through a polymer membrane is independent of inert gas pressure over the liquid and of hydrostatic liquid pressure. The rate increases linearly with temperature and decreases inversely with membrane thickness. In comparison, gas permeation through membranes obeys an Arrhenius temperature-rate law and is directly proportional to the differential gas pressure across the membrane. Van Amerongen's classic paper (Ref. 69) describes the influence of polymeric membrane molecular structure on gaseous diffusion rates. Briefly, any obstacle to the gaseous molecular diffusion, e.g., cross-linking, crystallinity, fillers, decrease diffusion rate. Plas-

ticization, whether "built in" or added by solvation, e.g., water vapor swelling of cellophane, increases the diffusion rate. One may not predict the permeation behavior of a polymer membrane from a knowledge of its chemical nature alone.

The reader should consult the reviews noted, especially that of Muraca, for a more complete understanding of the polymer permeation phenomenon. This phenomenon is of only peripheral importance to the overall ALPS design problem because metal membranes are very nearly completely impervious both to gases and to liquids, and this, of course, fulfills the ALPS requirements. If, as Vango has pointed out,<sup>7</sup> the basic ALPS design is changed so that a metal barrier separates the bladders, then permeation will stop at zero-g when a "skin" of permeant covers the bladder surface.

The appended Bibliography is fairly complete through 1963 and some of 1964. The few references published thus far on Teflon permeation behavior will be found in Appendix C, on Teflon.

<sup>7</sup>Personal communication, S. P. Vango.

## APPENDIX C

### Teflon

Teflon particles are made by the emulsion polymerization of monomer in the presence of (usually) a non-ionic wetting agent. The particles resemble striated peanuts when viewed by the electron microscope and they are about 200  $m\mu$  in diameter (Ref. 70, 71). The polymer is uniquely entirely crystalline (Ref. 72) and that prepared from melt exhibits a typical metallic fracture surface (Ref. 73-75). If an aqueous dispersion of particles is sprayed onto a surface it may subsequently be baked to sinter the particles into a contiguous coating (Ref. 76, 77). It is unlikely that the particles sinter other than at touching asperities (Ref. 78) in view of the remarkable viscosity of the melt (Ref. 79). Teflon melts at 327°C but must be raised to 380°C in order to form a true homogeneous melt (Ref. 72). During the sintering coating operation the wetting agent system stabilizer pyrolyzes to give the coat a brown color. The process has been applied to the manufacture of propellant bladders, protective and anti-slip coatings and capacitor foil, to mention only a few applications. The beginner in the field of Teflon coating should expect little advice or help from any organization now in the propellant bladder field. The overall technology is described roughly in typical Ref. 80, but actual practice can be made

successful only by trial-and-error. Because each successive Teflon coat is placed on the one beneath it the maximum practical thickness possible is about 30 mils because of thermal degradation of the first layers applied. Mud-cracking and holidays are the sure result if much more than ¼- to ½-mil thick coats are applied (Ref. 81).

The long term permeation of  $N_2O_4$  through Teflon sheet has been described (Ref. 82). The results suggest that a three-stage process occurs: initial mechanical (Knudsen) flow; swelling and blocking of pores; and final molecular diffusion.

Few studies of Teflon *per se* permeation behavior have been reported (Ref. 83). The copolymer of tetrafluoroethylene/hexafluoropropylene melts at 285°C to a true melt of  $10^8$  poise and has been treated by conventional molding techniques.

JPL Search No. 370 covers the literature on Teflon through October 1961; Search 369 covers Kel-F, similarly. The annual R&D conference proceedings, sponsored by the Office of Naval Research, summarizes technological applications.

## REFERENCES

1. "Propulsion," *Space Programs Summary No. 37-8*, Vol. II, pp. 141-145, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, April 1, 1961 (Confidential).
2. Koch, E. F., Porter, R. N., Stanford, H. B., and Weiner, R. S., "Advanced Liquid Propulsion System," *Space Programs Summary No. 37-15*, Vol. IV, pp. 149-151, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, June 30, 1962.
3. Mowers, R. E., "How the New Propellants Affect Plastics and Elastomers," *Materials in Design Engineering*, pp. 89-91, September 1959.
4. *Nitrogen Tetroxide, a Bibliography*, Nitrogen Division, Allied Chemical Corporation, New York, 1948.
5. Shore, J. J., *The Effect of Nitrogen Tetroxide on Some Halogenated Plastics*, Report MN-28 B-1, Engineering Division, Liquid Rocket Plant, Aerojet General Corporation, Sacramento, California, April 4, 1959.
6. Hollister, W. S., Compiler, *Compatibility of Elastomers With Liquid Propellants, An Annotated Bibliography*, Special Bibliography 61-64, Lockheed Missiles and Space Division, Sunnyvale, California, March 1962.
7. Green, J., et al., "Elastomers for Liquid Rocket Fuel and Oxidizer Application," *Industrial and Engineering Chemistry, Product Research and Development*, Vol. II, pp. 126-132, 1963.
8. Liberto, R. R., *Storable Propellant Data for the Titan II Program*, Report 8182-033001, Bell Aerosystems Company, Buffalo, New York, July 1961.
9. Vango, S. P., "Compatibility and Permeability of Nitroso Rubber," *Space Programs Summary No. 37-34*, Vol. IV, pp. 206-207, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, August 31, 1965.
10. Stannett, V., Szwarc, M., and Myers, A. W., *Evaluation of Gas Transmission Rates of Flexible Packaging Materials*, DA 19-129 QM123, Report AD-201-130, 126 pp., College of Forestry, State University of New York, Syracuse, New York, April 30, 1958.
11. Gillespie, L. H., et al., *New Design Data for Teflon*, Publication 10, Polychemicals Department, E. I. du Pont de Nemours & Company, Inc., Wilmington, Delaware, 1961.
12. Ephraim, F., *Inorganic Chemistry*, Eds. Thorne, P. C. L., and Roberts, E. R., 4th Ed., pp. 670-676, Interscience Publishers, New York, 1947.
13. Riebsomer, J. L., "The Reactions of Nitrogen Tetroxide With Organic Compounds," *Chemical Reviews*, Vol. 36, No. 2, pp. 157-233, 1945.
14. Hildebrand, J. H., and Scott, R. L., *Regular Solutions*, Appendix 5, p. 166, et seq., Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1962.
15. Audrieth, L. F., and Ackerson, B., *The Chemistry of Hydrazine*, John Wiley & Sons, Inc., New York, 1951.

## REFERENCES (Cont'd)

16. Liberto, R. R., "Research and Development on the Basic Design of Storable High-Energy Propellant Systems and Components," *Quarterly Progress Report No. 1*, 8086-933001, Table XXII, p. 71, Bell Aerosystems Company, Buffalo, New York, December 1959.
17. Boyd, W. K., and White, E. L., "Compatibility of Rocket Propellants With Materials of Construction," *DMIC Memorandum 65*, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, September 15, 1960.
18. Porter, R. N., and Stanford, H. B., *Propellant Expulsion in Unmanned Spacecraft*, Paper 868B, IAA A64-20451, SAE and ASME Air Transport and Space Meeting, New York, April 27-30, 1964.
19. Crank, J., "Diffusion With Rapid Irreversible Immobilization," *Transactions of the Faraday Society*, Vol. 53, pp. 1083-1089, 1957.
20. Roughton, F. J. W., "Diffusion Through Membranes Followed by Diffusion With Rapid Irreversible Immobilization in Another Medium," *Transactions of the Faraday Society*, Vol. 56, pp. 1085-1094, 1960.
21. Van Dolah, R. W., "Research on the Fire and Explosion Hazards Associated With New Liquid Propellant," *Progress Report No. 9*, AD-265,525, Explosive Research Laboratory, United States Bureau of Mines, Pittsburgh, Pennsylvania, May 1-August 31, 1961.
22. Perlee, H. E., Imhof, A. C., and Zabetakis, M. G., "Flammability Characteristics of Hydrazine Fuels in Nitrogen Tetroxide Atmospheres," *Journal of Chemical and Engineering Data*, Vol. 7, No. 3, pp. 377-379, 1962.
23. Van Dolah, R. G., et al., *Review of Fire and Explosion Hazards of Flight Vehicle Combustible*, Technical Report 61-278, AD-262,989, Aeronautical Systems Division, United States Bureau of Mines, Pittsburgh, Pennsylvania, April 1961.
24. Furno, A. L., Martindill, G. H., and Zabetakis, M. G., "Limits of Flammability of Hydrazine-Hydrocarbon Vapor Mixtures," *Journal of Chemical and Engineering Data*, Vol. 7, No. 3, pp. 375-376, 1962.
25. Skinner, C. B., Hedley, W. H., and Snyder, A. D., *Mechanism and Chemical Inhibition of the Hydrazine-Nitrogen Tetroxide Reaction*, AD-294,476, Monsanto Research Corporation, Dayton, Ohio, August 1961-October 1962.
26. Anderton, W. A., *The Reduction of Water Vapor Transmission Rates of Saran Films by Pigmentation*, DRML 174-10, Defence Research Board, Department of National Defence, Canada, October 1961.
27. Rolles, R., "Leaf Stabilization of Aluminum Paints," *Paint and Varnish Production*, Vol. 49, No. 10, 1959.
28. Osipow, L. I., *Surface Chemistry*, Chapter 10, Reinhold Publishing Corporation, New York, 1962.
29. Case, L. C., "Viscosity of Polytetrafluoroethylene Above the Melting Point," *Journal of Applied Polymer Science*, Vol. 3, No. 8, p. 254, 1959.
30. Fitzsimmons, V. G., and Zisman, W. A., *Microfiber Reinforcement of Polytetrafluoroethylene (Teflon)*, NRL 5724, AD-270,607, United States Research Laboratory, Washington, D. C., January 9, 1962.

## REFERENCES (Cont'd)

31. Witucki, R. M., *Design and Development of Hemispherical Rocket Fuel Expulsion Bladders*, ARC-R-156, Astro Research Corporation, Santa Barbara, July 31, 1964.
32. "Solvent-Oxidizer Mixes Are Explosive. Nitrogen Tetroxide Oxidizer and Partly Halogenated Solvents Form Explosive Mixtures, Study Shows," *Chemical and Engineering News*, p. 53, November 23, 1964.
33. "Chlorinated Solvents Explode with LOX," *Chemical and Engineering News*, p. 41, June 14, 1965.
34. Wikstrom, L. L., and Nobe, K., *Catalytic Decomposition of Nitrogen Dioxide*, Report 63-19, Engineering Department, University of California, Los Angeles, California, 1963.
35. Cahne, A., *Method of Coating a Metal Base With Polytetrafluoroethylene*, United States Patent 2,944,917, United States Department of Commerce, Washington, D. C., 1960.
36. Osdal, Le V., K., *Polytetrafluoroethylene Coating Compositions Having Improved Adhesion*, E. I. du Pont de Nemours & Company, Inc., United States Patent 2,562,117, United States Department of Commerce, Washington, D. C., July 24, 1951.
37. Panagrossi, A., and Hauser, R. L., *Lamination of Fluorine-Substituted Polyethylenes with or on Other Substances*, Connecticut Hard Rubber Company, United States Patent 2,705,691, United States Department of Commerce, Washington, D. C., April 5, 1955.
38. Sandt, B. W., and Wayne, P. J., *Bonding Tetrafluoroethylene Resins*, E. I. du Pont de Nemours & Company, Inc., United States Patent 2,914,438, United States Department of Commerce, Washington, D. C., November 24, 1959.
39. Vango, S. P., and Krasinsky, J. B., "Metal Plating of Teflon Sheet as a Means of Reducing Permeation," *Space Programs Summary No. 32-21*, Vol. IV, pp. 251-252, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, June 30, 1963.
40. Vango, S. P., and Krasinsky, J. B., "Continued Effort in Metal Plating of Teflon Sheet as a Means of Reducing Permeation," *Space Programs Summary No. 37-23*, Vol. IV, pp. 283-285, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, October 31, 1963.
41. Schonhorn, H., "Generalized Approach to Adhesion Via the Interfacial Decomposition of Amphipathic Molecules. Adhesion of Polyethylene to Aluminum," *Journal of Applied Polymer Science, Part A*, Vol. 1, pp. 2343-2359, 1963.
42. Covert, R. A., and Rabinowicz, E., *An Investigation of Metallic Thin Film Composite Materials*, ASD-TDR-62-617, Aeronautical Systems Division, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio, June 1962.
43. Swartout, J. T., and Setterholm, V. C., *Effect of Number of Plies on the Tear Resistance of Paper*, FPL-05, AD-407,578, Forest Products Laboratory, Agricultural Department Forest Service, Madison, Wisconsin, May 1963.

## REFERENCES (Cont'd)

44. Coplan, M. J., Freeston, W. D., Jr., and Powers, D. H., Jr., *Flexible, Low Porosity, Woven Metallic Materials*, ASD-TDR-61-677, Aeronautical Systems Division, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio, November 1961.
45. Prins, W., and Hermans, J. J., "Theory of Permeation Through Metal Coated Polymer Films," *The Journal of Physical Chemistry*, Vol. 63, p. 713, 1959.
46. Forbes, F. W., *Expandable Structures for Aerospace Applications*, STAR N63-14222, Flight Accessories Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Ohio, May 19, 1963.
47. Robins, B. N., et al., *Spirally Wound Covering for Popcorn Containers*, United States Patent 2,815,883, United States Department of Commerce, Washington, D. C., 1957.
48. Hinshelwood, C. N., "The Influence of Substituents on the Oxidation of Hydrocarbons," *Discussions of the Faraday Society*, Vol. 10, pp. 266-268, 1951.
49. Green, J., and Levine, N. B., *Elastomeric and Compliant Materials for Contact with Liquid Rocket Fuels and Oxidizers*, ASD Technical Report 61-76, AD-269,310, Aeronautical Systems Division, Air Force Systems Command, United States Air Force, Wright-Patterson Air Force Base, Ohio, September 1961.
50. Simha, R., "Mechanism and Kinetics of Chain Degradation," *Proceedings of the International Symposium on Macromolecular Chemistry*, pp. 250-264, Pergamon Press, New York, 1957.
51. Grassie, N., *Chemistry of High Polymer Degradation Processes*, Interscience Publishers, New York, 1956.
52. *Polymer Degradation Mechanisms: Proceeding of the NBS Semi-Centennial Symposium, September 24-26, 1951*, National Bureau of Standards Circular 525, National Bureau of Standards, Washington, D. C., 1953.
53. Patrick, C. R., "Thermochemistry and Thermodynamics of Fluorocarbons," *Tetrahedron*, Vol. 4, pp. 26-35, 1958.
54. Case, L. L., "Viscosity of Polytetrafluoroethylene Above the Melting Point," *Journal of Applied Polymer Science*, Vol. 3, No. 8, p. 254, 1960.
55. Mowers, R. E., "How the New Propellants Affect Plastics and Polymers," *Materials in Design Engineering*, Vol. 50, p. 91, 1959.
56. Reilly, M. W., and Brown, H. C., "Reactions of the Perfluoronitriles. II. Synthesis of 2,4,6-tris-(Perfluoroalkyl)-1,3,5-Triazines," *The Journal of Organic Chemistry*, Vol. 22, p. 698, 1957.
57. Brown, H. C., "Thermally Stable Polymers from Condensation Polymerization of Perfluoroalkylamidines," *Journal of Polymer Science*, Vol. 44, pp. 9-22, 1960.
58. Husted, D. R., *Perfluoroalkylamidines*, Minnesota Mining and Manufacturing Company, United States Patent 2,676,985, United States Department of Commerce, Washington, D. C., April 27, 1954.
59. Barr, D. A., Haszeldine, R. N., and Willis, C. J., "New Elastomer Containing Fluorine," *Proceedings of the Chemical Society (London)*, Vol. 1959, p. 230, 1959.

## REFERENCES (Cont'd)

60. Banks, R. E., and Haszeldine, R. N., "Perfluoroalkylnitroso-compounds from Perfluoroacyl Nitrites," *Proceedings of the Chemical Society (London)*, Vol. 1959, pp. 64-65, 1961.
61. Banks, R. E., and Haszeldine, R. N., "Polyfluoroalkyl Derivatives of Metalloids and Non Metals," *Advances in Inorganic Chemistry and Radiochemistry*, Eds. Emelus, H. J., and Sharpe, A. G., Vol. 3, pp. 348-353, Academic Press, New York, 1961.
62. Vango, S. P., "Compatibility and Permeability of Nitroso Rubber," *Space Programs Summary No. 37-34*, Vol. IV, pp. 206-207, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, April 31, 1965.
63. Muraca, R. F., *Investigation of the Space Storability of Pressurizing Gases*, NAS 7-105, Stanford Research Institute, Menlo Park, California, February 18, 1963.
64. Sneck, H. J., *A Survey of Gas Permeation Through Metals and Polymers*, Bearing and Lubrication Center, General Engineering Laboratory, General Electric Company, Schenectady, New York, August 28, 1962.
65. Tuwiner, S. B., Miller, L. P., and Brown, W. F., "Diffusion and Membrane Technology," *American Chemical Society Monograph Series No. 156*, New York, 1962.
66. Sourirajan, S., "The Mechanism of Demineralization of Aqueous Sodium Chloride Solutions by Flow, Under Pressure, Through Porous Membranes," *Industrial and Engineering Chemistry, Fundamentals*, Vol. 2, pp. 51-55, New York, 1963.
67. Henley, E. J., Li, N. N., and Long, R. B., "Membrane Separation Processes," *Industrial and Engineering Chemistry*, Vol. 57, No. 3, pp. 18-29, 1965.
68. Vromen, B. H., "Dialysis and Electrodialysis," *Industrial and Engineering Chemistry*, Vol. 54, No. 6, pp. 20-28, 1962.
69. Van Amerogen, G. J., "Influence of Structure of Elastomers on Their Permability to Gases," *Journal of Polymer Science*, Vol. 5, No. 3, pp. 307-332, 1950.
70. Grimaud, E., et al., "Dispersions de Polytetrafluoroethylene," *Journal of Polymer Science*, Vol. 31, No. 123, p. 525, 1958.
71. Lontz, J. F., and Happoldt, W. B., Jr., "Teflon Tetrafluoroethylene Resin Dispersion," *Industrial and Engineering Chemistry*, Vol. 44, No. 8, p. 1800, 1952.
72. Bunn, C. W., Cobbold, A. J., and Palmer, R. P., "The Fine Structure of Polytetrafluoroethylene," *Journal of Polymer Science*, Vol. 28, No. 117, pp. 365-376, 1958.
73. Butenuth, G., "Zur Struktur Von Polytetrafluoroathylen," *Verhandlungsber Kolloid-Ges*, Vol. 18, pp. 168-179, 1958.
74. Duay, H. D., *Fine Structure Study of Several Plastic Polymers*, Report 6124-1, United States Army Engineer Research and Development Labs., Corps of Engineers, Fort Belvoir, Virginia, June 10, 1958.
75. Schimel, G., "Elektronenmikroskopische Untersuchung an Polytetrafluoroathylen," *Naturwissenschaften*, Vol. 46, p. 13, 1959.
76. *Teflon Tetrafluoroethylene Resin, Design and Engineering Data*, Report A-3063, Polychemicals Department, E. I. du Pont de Nemours & Company, Inc., Wilmington, Delaware, 1956.

## REFERENCES (Cont'd)

77. *Teflon TFE-Fluorocarbon Resin Finishes*, Industrial Finishes Technical Bulletin, Bulletin No. 1, 10th ed., A-21350, Finishes Division, E. I. du Pont de Nemours & Company, Inc., Wilmington, Delaware, September 1961.
78. Kargin, A. A., et al., "Electron Microscopic Investigation of the Mechanism of Sintering of Polytetrafluoroethylene" (in Russian), *Vysokonolekulyarnye Soedineniya*, Vol. 1, pp. 1143-1147, 1959.
79. Case, L. C., "Viscosity of Polytetrafluoroethylene Above the Melting Point," *Journal of Applied Polymer Science*, Vol. 3, No. 8, p. 254, 1960.
80. *Process of Applying Thin Films of Polytetrafluoroethylene Resins on Aluminum Alloy Surfaces*, NAVWEPS OD 23684, AD-265,238, Naval Ordnance Labs., White Oak, Maryland, August 15, 1961.
81. Estey, W., et al., *Production Refinement of Very Thin Gauge Teflon Film*, Quarterly Report No. 3, AD-145,758, General Engineering Labs., American Machine and Foundry Company, Greenwich, Connecticut, October 1957.
82. Bauman, A. J., and Stembridge, C. W., "A Continuous-Recording Automatic Permeameter, with Application to the Permeation of Nitrogen Tetroxide Through Teflon," *Space Programs Summary No. 37-30*, Vol. IV, pp. 206-208, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, December 31, 1964.
83. Peirce, E. C., "Diffusion of Oxygen and Carbon Dioxide Through Teflon Membranes," *A.M.A. Archives of Surgery*, Vol. 77, No. 6, p. 938, December 1958.



## BIBLIOGRAPHY

- Barrer, R. M., "Some Properties of Diffusion Coefficients in Polymers," *The Journal of Physical Chemistry*, Vol. 61, p. 178, 1957.
- Barrer, R. M., and Skirrow, G., "Transport and Equilibrium Phenomena in Gas-Elastomer Systems. I. Kinetic Phenomena," *Journal of Polymer Science*, Vol. 3, p. 549, 1948.
- Barrer, R. M., and Skirrow, G., "Transport and Equilibrium Phenomena in Gas-Elastomer Systems. II. Equilibrium Phenomena," *Journal of Polymer Science*, Vol. 3, p. 564, 1948.
- Barton, R. S., *The Permeability of Some Plastic Materials to H<sub>2</sub>, He, N<sub>2</sub>, O<sub>2</sub>, and A*, Report AERE-M599, Atomic Energy Research Establishment, Harwell, Burks, England, February 1960.
- Bearman, R. J., and Koenig, F. O., "Thermo-Osmosis of Rare Gases Through a Rubber Membrane," *The Journal of the American Chemical Society*, Vol. 78, p. 691, 1956.
- Bhargava, R., Rogers, C. E., Stannett, V., and Szwarc, M., *Studies in the Gas and Vapor Permeability of Plastic Films and Coated Papers. Part IV*, Technical Association of the Pulp and Paper Industry, Vol. 40, p. 564, 1957.
- Binning, R. C., Lee, R. J., Jennings, J. F., and Martin, E. C., "Separation of Liquid Mixture by Permeation," *Industrial and Engineering Chemistry*, Vol. 53, No. 1, pp. 45-50, 1961.
- Brandt, W. W., "The Effect of Polymer Density on the Diffusion of Ethane in Polyethylene," *Journal of Polymer Science*, Vol. 41, p. 403, 1959.
- Brown, W. E., and Sauber, W. J., "Gas Transmission by Plastic Films," *Modern Plastics*, Vol. 36, No. 12, pp. 107, 110, 112-114, 116, and 190, August 1959.
- Brubaker, D. W., and Kammermeyer, K., "Separation of Gases by Means of Permeable Membranes," *Industrial and Engineering Chemistry*, Vol. 44, No. 6, pp. 1465-1474, 1952.
- Brubaker, D. W., and Kammermeyer, K., "Separation of Gases by Means of Permeable Membranes," *Industrial and Engineering Chemistry*, Vol. 45, No. 5, pp. 1148-1152, 1953.
- Brubaker, D. W., and Kammermeyer, K., "Separation of Gases by Plastic Membranes," *Industrial and Engineering Chemistry*, Vol. 46, p. 733, 1954.
- Cartwright, L. C., "Measurement of the Gas Permeability of Sheet Materials," *Analytical Chemistry*, Vol. 19, No. 6, pp. 393-396, 1947.
- Cutler, J. A., and McLaren, A. D., "Permeation and Sorption of Organic Vapors by High Polymers," *Tappi* (Technical Association of the Pulp and Paper Industry), Vol. 36, No. 9, pp. 423-425, 1953.
- Denbigh, K. G., and Raumann, G., "The Thermo-Osmosis of Gases Through a Membrane. I. Theoretical," *Proceedings of the Royal Society (London)*, Series A210, p. 377, 1952.
- Denbigh, K. G., and Raumann, G., "The Thermo-Osmosis of Gases Through a Membrane. II. Experimental," *Proceedings of the Royal Society (London)*, Series A210, p. 518, 1952.

## BIBLIOGRAPHY (Cont'd)

- Dietrick, H. J., and Meeks, W. W., "Permeability of Various Polymers to 90% Hydrogen Peroxide," *Journal of Applied Polymer Science*, Vol. 2, No. 5, p. 231, 1959.
- Doty, P. M., Aiken, W. H., and Mark, H., "Temperature Dependence of Water Vapor Permeability," *Industrial and Engineering Chemistry*, Vol. 38, p. 788, 1946.
- Edwards, J. D., and Pickering, S. F., *Permeability of Rubber to Gases*, United States Bureau of Standard Scientific Paper 16, National Bureau of Standards, Washington, D. C., 1920.
- Eisenmann, J. L., *Purification of Organic Compounds by Membrane Permeation*, AD-263,172, First Bimonthly Progress Report Contract DA-18-108-Cmi-6626, Ionics Incorporated, Cambridge, Massachusetts, September 1961.
- Frank, R. C., "Gases-in-Solids," *International Science and Technology*, pp. 53-59, Bibliography, p. 89, September 1962.
- Frisch, H. L., "Gas Permeation Through Membranes Due to Simultaneous Diffusion and Convection," *The Journal of Physical Chemistry*, Vol. 60, p. 1177, 1956.
- Harris, J. T., and Stimler, F. J., "Expandable Structures for Space," *Astronautics*, Vol. 6, No. 4, p. 30, 1961.
- Henderson, R., and Wallace, G. A., "A Simple Apparatus for Determining Gas Permeability of Flexible Films," *Food Technology*, No. 10, p. 636, 1956.
- Hsieh, P. Y., *A Study of the Encapsulation Applicable to Liquid Rocket Fuel*, NCR Interim Report No. 2, Contract No. nr 2848(00), National Cash Register Company, Dayton, Ohio, January 1961.
- Jaumot, F. E., Jr., *A Bibliography of Diffusion of Gases, Liquids, and Solids in Solids, 1890 to 1955*, USAEC Report TID-3071, Atomic Energy Commission, Oak Ridge, Tennessee, April 1958.
- Jupa, J. A., "Fluorocarbon Plastics Today," *Product Engineering*, p. 168, October 1954.
- Kammermeyer, K., "Vapor Transfer Through Barriers," *Industrial and Engineering Chemistry*, Vol. 50, p. 697, 1958.
- Kammermeyer, K., and Brubaker, D. W., "Membrane Separation in the Gaseous Phase," *Chemical Engineering Progress*, Vol. 50, No. 11, pp. 560-564, 1954.
- Kammermeyer, K., and Wyrick, D. D., "Effect of Adsorption in Barrier Separation," *Industrial and Engineering Chemistry*, Vol. 50, p. 1309, 1958.
- Keeson, W. H., *Helium*, Elsevier, Amsterdam, Holland, pp. 125-132, 1942.
- Klute, C. H., "Diffusion of Small Molecules in Semicrystalline Polymers. II. The Permeability of Unoriented Polymer Film," *Journal of Polymer Science*, Vol. 51, pp. 307-317, 1959.
- Klute, C. H., and Franklin, P. J., "The Permeation Water Vapor Through Polyethylene," *Journal of Polymer Science*, Vol. 32, p. 161, 1958.
- Korte-Falinski, M., "Permeabilite des Matieres Plastiques a la Vapeur d'Eau," *Publications Scientifiques et Techniques du Ministere de l'Air (France)*, No. N. T. 124, Service de Documentation et d'Information Technique de l'Aeronautique, Paris, France, 74 pp., 1963.

## BIBLIOGRAPHY (Cont'd)

- Kumins, C. A., and Roteman, J., "Diffusion of Gases and Vapors Through Polyvinyl Chloride-Polyvinyl Acetate Copolymer Films. I. Glass Transition Effect," *Journal of Polymer Science*, Vol. 55, pp. 638-698, 1961.
- Kumins, C. A., and Roteman, J., "Diffusion of Gases and Vapors Through Polyvinyl Chloride-Polyvinyl Acetate Copolymer Films. II. The Effect of Polymer Segment Mobility," *Journal of Polymer Science*, Vol. 55, pp. 699-711, 1961.
- Lasoski, S. W., Jr., and Cobbs, W. H., Jr., "Moisture Permeability of Polymers. I. Role of Crystallinity and Orientation," *Journal of Polymer Science*, Vol. 36, p. 21, 1959.
- Lundberg, J. L., Wilk, M. B., and Huvett, M. J., "Solubilities and Diffusivities of Nitrogen in Polyethylene," *Journal of Applied Physics*, Vol. 31, p. 1131, 1960.
- Meyer, J. A., Rogers, C., Stannett, V., and Szwarc, M., *Studies in the Gas and Vapor Permeability of Plastic Films and Coated Papers. Part III*, *Tappi*, Vol. 40, p. 142, 1957.
- Michaels, A. S., and Parker, R. B., Jr., "Sorption and Flow of Gases in Polyethylene," *Journal of Polymer Science*, Vol. 41, pp. 53-71, 1959.
- Myers, A. W., Meyer, J. A., Rogers, C. E., Stannett, V., and Szwarc, M., "Studies in the Gas and Vapor Permeability of Plastic Films and Coated Papers. Part VI," *Tappi*, Vol. 44, p. 58, 1961.
- Myers, A. W., Rogers, C. E., Stannett, V., and Szwarc, M., "Studies in the Gas and Vapor Permeability of Plastic Films and Coated Papers. Part V," *Tappi*, Vol. 41, p. 716, 1958.
- Myers, A. W., Rogers, C. E., Stannett, V., and Szwarc, M., "The Permeability of Some Graft Copolymers of Polyethylene to Gases and Vapors," *Journal of Applied Polymer Science*, Vol. 4, No. 11, p. 159, 1960.
- Myers, A. W., Rogers, C. E., Stannett, V., and Szwarc, M., "Permeability of Polyethylene to Gases and Vapors," *Modern Plastics*, No. 34, p. 157, 1957.
- Myers, A. W., Stannett, V., and Szwarc, M., "The Permeability of Polypropylene to Gases and Vapors," *Journal of Polymer Science*, No. 35, p. 285, 1959.
- Myers, A. W., Tammela, V., Stannett, V., and Szwarc, M., "Permeability of Chlorotrifluoroethylene Polymers," *Modern Plastics*, No. 37, p. 139, June 1960.
- Nagel, B. H., *Annotated Bibliography on Permeation of Gases Through Solids*, Report EM-5883, Autonetics Corporation, Newport Beach, California, October 12, 1959.
- Norton, F. J., "Rare Gas Permeation Through Polymers," *The Journal of Chemical Physics*, Vol. 22, p. 1145, 1954.
- Norton, F. J., "Permeation of Gases Through Solids," *Journal of Applied Physics*, Vol. 28, p. 34, 1957.
- Othmer, D. F., and Frohlick, G. J., "Correlating Permeability Constants of Gases Through Plastic Membranes," *Industrial and Engineering Chemistry*, Vol. 47, pp. 1034-1040, 1955.
- Park, W. R. R., "Semimicro Gas Permeability Apparatus for Sheet Material," *Analytical Chemistry*, Vol. 29, p. 1897, 1957.

**BIBLIOGRAPHY (Cont'd)**

- Parmelee, H. M., "Permeability of Plastic Films to Refrigerant 12 and Nitrogen," *Refrigerating Engineering*, Vol. 66, No. 2, p. 35, 1958.
- Pilar, F. L., "The Flow of Gases Through High Polymer Films in Equilibrium With Sorbed Vapors," *Journal of Polymer Science*, Vol. 55, pp. 205-215, 1960.
- Prager, S., "The Calculation of Diffusion Coefficients from Sorption Data," *The Journal of Chemical Physics*, Vol. 19, p. 537, 1951.
- Rogers, C. E., Meyer, J. A., Stannett, V., and Szwarc, M., "Studies in the Gas and Vapor Permeability of Plastic Films and Coated Papers. Part I," *Tappi*, Vol. 39, p. 737, 1956.
- Rogers, C. E., Meyer, J. A., Stannett, V., and Szwarc, M., "Studies in the Gas and Vapor Permeability of Plastic Films and Coated Papers. Part II," *Tappi*, Vol. 39, p. 741, 1956.
- Rogers, C. E., Stannett, V., and Szwarc, M., "Studies in the Gas and Vapor Permeability of Plastic Films and Coated Papers. Part VII," *Tappi*, Vol. 44, p. 715, 1961.
- Rogers, C. E., Stannett, V., and Szwarc, M., "Permeability Valves," *Industrial and Engineering Chemistry*, Vol. 49, p. 1933, 1957.
- Rogers, C. E., Stannett, V., and Szwarc, M., "The Sorption, Diffusion, and Permeation of Organic Vapors in Polyethylene," *Journal of Polymer Science*, Vol. 55, pp. 61-82, 1960.
- Rosen, B., "A Recording Sorption Kinetics Apparatus," *Journal of Polymer Science*, Vol. 35, p. 335, 1959, Transactions of Society of Petroleum Engineers of AIME, p. 153, October 1961.
- Sarge, T. W., "Determination of Gas Permeability of Saran Films," *Analytical Chemistry*, No. 19, p. 396, 1947.
- Schulz, G. V., and Gerrens, H., "Diffusion und Kapillarströmung indifferenten Gase im glasartigen Polystyrol," *Zeitschrift für Physikalische Chemie, Neue Folge*, Vol. 7, pp. 182-206, Frankfurt, Germany, 1956.
- Stokoe, A. L., and Wilkins, P. G., *The Permeability of Elastomers to Organic Fluids*, Technical Memo ERDE 6/m/62, AD-275,369, Explosives Research and Development Establishment, Waltham Abbey, Ministry of Aviation, Essex, Great Britain, February 1962.
- Storner, W. C., "Compatibility of Freon 114 Used in Mercury Support Equipment With Various Hose Materials," *Aerospace Engineering*, p. 28, June 1961.
- Stout, L. E., Geisman, R., and Mozley, J. M., Jr., "Diffusivity of Gases Through Synthetic Elastomer Diaphragms," *Chemical Engineering Progress*, Vol. 44, pp. 219-228, 1948.
- Sweeney, R. F., and Rose, A., *Research Study of Physicochemical Technique for the Purification of Organic Compounds*, AD-266,921, Nineteenth Bimonthly Progress Report, Contract DA-18-108-405-CML-176, Applied Science Laboratories, Inc., State College, Pennsylvania, November 1961.

### BIBLIOGRAPHY (Cont'd)

Van Amerongen, G. J., "The Permeability of Different Rubbers to Gases and Its Relation to Diffusivity and Solubility," *Journal of Applied Physics*, Vol. 17, p. 927, 1946.

Vango, S., *Determination of Permeability of Cast Teflon Sheet to Nitrogen Tetroxide and Hydrazine*, Technical Memorandum No. 33-35, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, August 25, 1961.

Waack, R., et al., "Permeability of Polymer Films to Gases and Vapors," *Industrial and Engineering Chemistry*, Vol. 47, p. 2524, 1955.