STRENGTH OF INORGANIC GLASS

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DEDICATION – CHRISTIAN JANSSEN

While he was personally well-known to his European colleagues and to his co-workers in Corning, U.S.A., before this meeting, Chris Janssen was known to many of us only through his scientific work and publications. Since he was the first of the participants to arrive for the meeting, I had the opportunity to spend some time during the first few days to get to know Chris, walking the beaches with him discussing the science of both glass and gliding. Although he did not make a formal presentation he took a very active part in the meeting and certainly contributed greatly to its success. He will be missed by us all.

Christian Janssen died on July 7, 1983, in Madrid, Spain following a glider accident the previous day. While landing in an open field at dusk, after an 8 hour journey, his glider crashed against some logs. He was 44 and had been flying gliders and airplanes since he was 17. He is survived by his twin brother and his parents.

He was born in 1939, in Valenciennes in the north of France. He obtained his "Diplome d' Ingenieur" in 1964, from the School of Mining at the University of Liege, Belgium. After one year as Assistant to Professor Calembert in geology, he joined the French Atomic Energy Commission, Laboratory at Bruyeres-le-Chatel, in the Physical Metallurgy Group. In 1970, he joined the Research Laboratory of Sovirel, the French subsidiary of Corning Glass Works, now the Research and Development Laboratory, Corning Europe. He became involved in fracture mechanics, particularly of brittle materials and contributed to the success of many Corning Glass Works products. He wrote many publications and was one of the editors of "La Fatigue des Metaux," one of the basic French books on materials fatigue.

C. R. K.

PREFACE

In June of 1981 Alan Chynoweth and Paul Fleury, both then with AT&T Bell Laboratories, inquired of the editor whether there was a topic in the field of glass which was an appropriate one for a NATO "Workshop" — or as they were initially called — "Advanced Research Institutes." These meetings were meant to be, and consequently ours was designed to be — *essentially* a Gordon Conference. The principal difference was in this case, that there would be publication of the proceedings. As in the case of a Gordon Conference, a select group of "experts" in a given field would be assembled in a more or less out of the way location, e.g., away from "civilized distractions" for about one week. The reason for the rule against publication in the case of the Gordon Conferences is to encourage a high level of speculative discussion, and the resultant stimulation of the assembled experts. In the case of the NATO Workshops, publication is intended to enlighten a rather larger population and in particular to teach those in NATO countries with little or no expertise in a given field. Obviously it is hoped that this does not inhibit discussion.

In a field as old as glass science (and/or technology), there are usually a great many unsolved problems, and unanswered questions. Although there are many reasons for this, two of the most important, and those that might benefit from such a NATO meeting are:

1. The lack of such periodic assemblies of experts, and at least as important
2. The lack of documentation and dissemination of the accomplishments of such a meeting.

The topic "The Strength of Inorganic Glass" was chosen partly because of my interest in the field at the time, but more importantly because of the following:

1. The vital importance of mechanical strength and reliability in the development of glass "lightguides" and the accompanying activity and progress in this area.
2. The very high level of interest and activity in the field of fracture mechanics especially as applied to inorganic glasses, and

3. The importance to the glass container industry, of some sort of breakthrough in mechanical behavior at this time because of increasing pressure from non-glass containers.

A glance at the Table of Contents will give an idea of the make-up of the meeting. However, a reprinting here of a modified and somewhat abridged set of guidelines which I initially provided to prospective attendees may give some better insight into what we hoped to accomplish.

"This is a brief description of my view of what the various sessions should cover —

1. *History*. This should illustrate where we have gone wrong in the past, as well as remind us of some of the remarkable achievements of early workers. It should enable us to put our own work into perspective.

2. *Theory*. This in principle could cover most of the topics at the meeting. However, I would hope that by means of some simple models, to get some idea of the kinds of numbers to be expected for the strengths of inorganic glasses and what parameters control these strengths. A review of the behavior of polymeric and metallic glasses should also be useful for comparison.

3. *Surface chemistry*. Before getting involved in the details of strength, an introduction to surface chemistry as it might influence strength is necessary. Discussions of both adsorption and layer formation, as well as indications of useful analytical techniques for their study should set the stage for later sessions. Very little interaction between specialists in surface chemistry and fracture is evident in the literature. This should be rectified.

4. *Crack velocity*. The simplest way to study the effects of environment on fracture behavior is through crack velocity measurements. Detailed models for subcritical crack growth have been proposed on the basis of this kind of measurement. A summary of our understanding of these simpler experiments will be useful before considering more complex fracture systems.

5. *Indentation*. The analysis of stress fields, deformation, flow and fracture in simply-loaded systems is essential to the use of crack velocity information in explaining fracture behavior. Static and dynamic indentation plus scratching experiments illustrate the complexity of practical systems.

6. *Flaws*. Analysis of the production and growth of flaws in very simple systems must now be extended by the consideration of "real flaws" — their observation, geometry and modification in the presence of various chemical and mechanical perturbations.

7. *Strength and fatigue*. Actual strength and delayed strength data as a function of surface treatment, environment, temperature, time and glass

composition can be discussed on the basis of all of the previous sessions. It is hoped that a clearer picture of the behavior of "real flaws" in real situations will emerge.

8. *Real world strength.* All of the previous discussions should now be applied to analyzing the practical strength of glass articles of commerce. Some examples of successes, failures and challenges should allow some conclusions as to future directions to be drawn.

9. *Strengthening.* Following the previous discussion, it should be clear that an increase in the practical strength by the use of surface compressive stresses would be very useful. This session describes theoretical and practical aspects of this effect.

10. *Fibers.* In some cases it it felt that "perfect" fiber surfaces have been studied. The possibility of achieving this perfect surface as well as its sensitivity to external factors is important to the understanding of fiber behavior. Effects of drawing and testing parameters and glass composition on the measured strength are of great importance.

We should now have come full circle, and a discussion comparing "perfect fiber" behavior and theoretically predicted behavior should be in order."

Thus the primary purpose of the meeting was to capitalize on the high level of activity in traditional areas of the strength of glass, as well as the newer activity in fracture mechanics and optical fibers. Some of the secondary reasons, were the following:

1. Provision of a data base for workers in the field.
2. Retrieval of "lost" information — both 'older' work and work published in languages other than English. Although it had originally been planned to have a review of some of the more outstanding work from Eastern bloc countries, this did not materialize. While some of this work will be referred to in my concluding remarks, it is hoped that the recognition of this gap will aid in rectifying it.

Finally, not everyone who was invited was able to attend the Workshop, and unfortunately, not everyone who should have attended was invited. For the second of these circumstances I am to blame and for this I apologize. To all of those who contributed to the success of these proceedings and the meeting itself — all of those who took part in early planning sessions or in informal discussions, I give my sincere thanks. I would also like to thank Joe Hagan, Dave Martin, Charlie McKinnis and Sidney Budd, who could not attend but submitted manuscripts for publication. My special thanks go to Dr. Rui de Almeida, of the Intituto Superior Técnico, the University of Lisbon for

his invaluable assistance with the organization of meeting in general, but in particular with the local arrangements.

This book has been formally dedicated to Chris Janssen. However a brief word must be said about those 'toilers in the field' — our predecessors who did such remarkable work in a very complicated and difficult field — both experimentally and theoretically — Griffith, Preston, Smekal, Turner, Orowan, Gurney, Shand, Mould, Otto and many, many others. Without their pioneering work, it goes without saying, the advances recorded in this book would not have been possible.

C. R. Kurkjian
Murray Hill
August, 1985

CONTENTS

A LOOK AT THE HISTORY OF GLASS STRENGTH

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"The investigator should have a robust faith and yet not believe"

(Claude Bernard. "Introduction à la médecine experimentale," 1865)

A descriptive and personal account is given of the stages in the development of our knowledge and ideas concerning the fracture behaviour of glass: from the age of Griffith through the dark ages to a renaissance but without, as yet, an enlightenment.

I. EARLY HISTORY

Records of the earliest measurements of the strength of glass, like those of the first processes used in its manufacture, seem to be lost to ancient history. Some information exists on the development of ideas on the strength of materials in general: notebooks left by Leonardo da Vinci (1452-1519) reveal that he measured the breaking loads for iron wires and Galileo (1564-1642), in his "Two New Sciences", recapitulates many of his own observations on the mechanics of elastic bodies. He recognized that the strength of a bar loaded in tension should be proportional to its cross-section area and correctly identified the most likely position for the fracture of a simple cantilever beam, although he did not appreciate the nature of what we should now call the stress distribution over the cross-section.

Glass was certainly used by many of the sixteenth and seventeenth century natural philosophers in their experiments on the mechanics of solid bodies: Hooke (1635-1703) included glass among the many materials he examined before publishing, in 1678, the famous law later expressed as 'stress is proportional to strain'; Mariotte (1620-1684) used wooden and glass rods in cantilever bending to show that Galileo's calculations overestimated the breaking loads.

By the nineteenth century the utility and importance of distinguishing between the purely elastic and the plastic behaviour of solids was widely recognized and this often led to the selection of glass as a model material when it was desired to avoid effects due to 'permanent set'. Fairbairn and Tate[1] chose glass for some basic experiments, reported in 1859, related to their work on the design of boiler tubes; they noted the added advantage that glass provided tubes and spherical shells "of more perfect form". Their experiments were designed to ascertain the relationship between the critical external pressure required to cause the collapse of a tube and the breaking strength of the material. Incidentally, they complained of a paucity of reliable figures for the tenacity of glass and reported some of their own measurements.

II. THE AGE OF GRIFFITH

Griffith's work[2,3] provides the obvious starting point for a review of the modern scientific investigation of the strength of glass. Indeed there can be few papers with more citations. However, the frequent claims of a seminal relationship between Griffith's work and that on the strength of glass ever since are rather misleading. Although Preston[4] and Milligan[5] evidently realized the significance of the work in the context of the practical strength of glass, its implications were more often ignored and much that was important or useful in the original paper soon dropped out of sight. Judging by the claims regarding its content, few authors citing the 'Phil. Trans. - 1920' paper could actually have read it and many major review articles in the 1930's and 1940's give seriously distorted accounts of the work. The 1920 paper contains some fascinating detail and, I believe, offered valuable ideas which were ignored, became lost and had to be rediscovered many years later.

In his introduction, Griffith records that his original concern was with the fatigue rupture of metals, particularly "the effect surface treatment - such as, for instance, filing, grinding or polishing - on the strength of metallic machine parts subjected to alternating or repeated loads." The stresses at the tip of a surface notch could be calculated using the earlier results of Inglis,[6] but the then commonly used criteria for the brittle rupture of solids (maximum tensile stress or maximum strain exceeding a critical value) yielded predictions about the effects of surface scratches which were in conflict with the observed behaviour. It was for this reason that Griffith sought an alternative criterion for rupture. He expressed the now famous energy-balance criterion in the somewhat elaborate style of the times: that rupture would occur "if the system can pass from the unbroken to the broken