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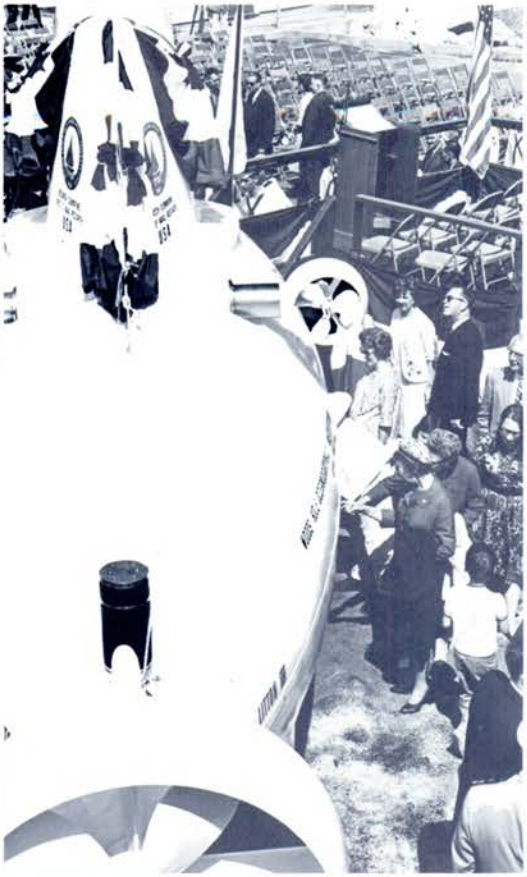
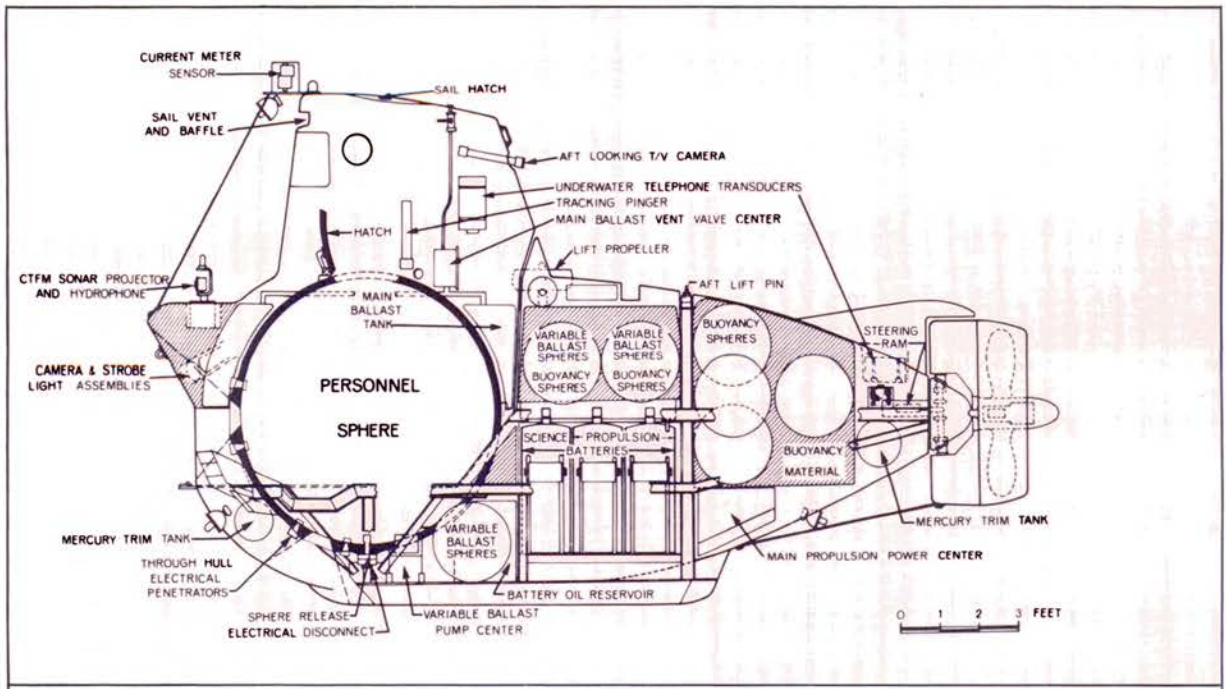
Predicting Crises

See Page 2

Commissioning Date
5 June 1964





Celebrating her 1000th dive, Alvin explored the floor of the Pacific Ocean north of the equator in January, 1980. See "Research Note" on page 43.

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ARTICLES

DEPARTMENTS

About Our Cover

As global tensions develop, the need to monitor and evaluate events leading to critical situations becomes increasingly significant, especially to decision makers who rely on early warning that a crisis is likely to occur. *See p. 2.*

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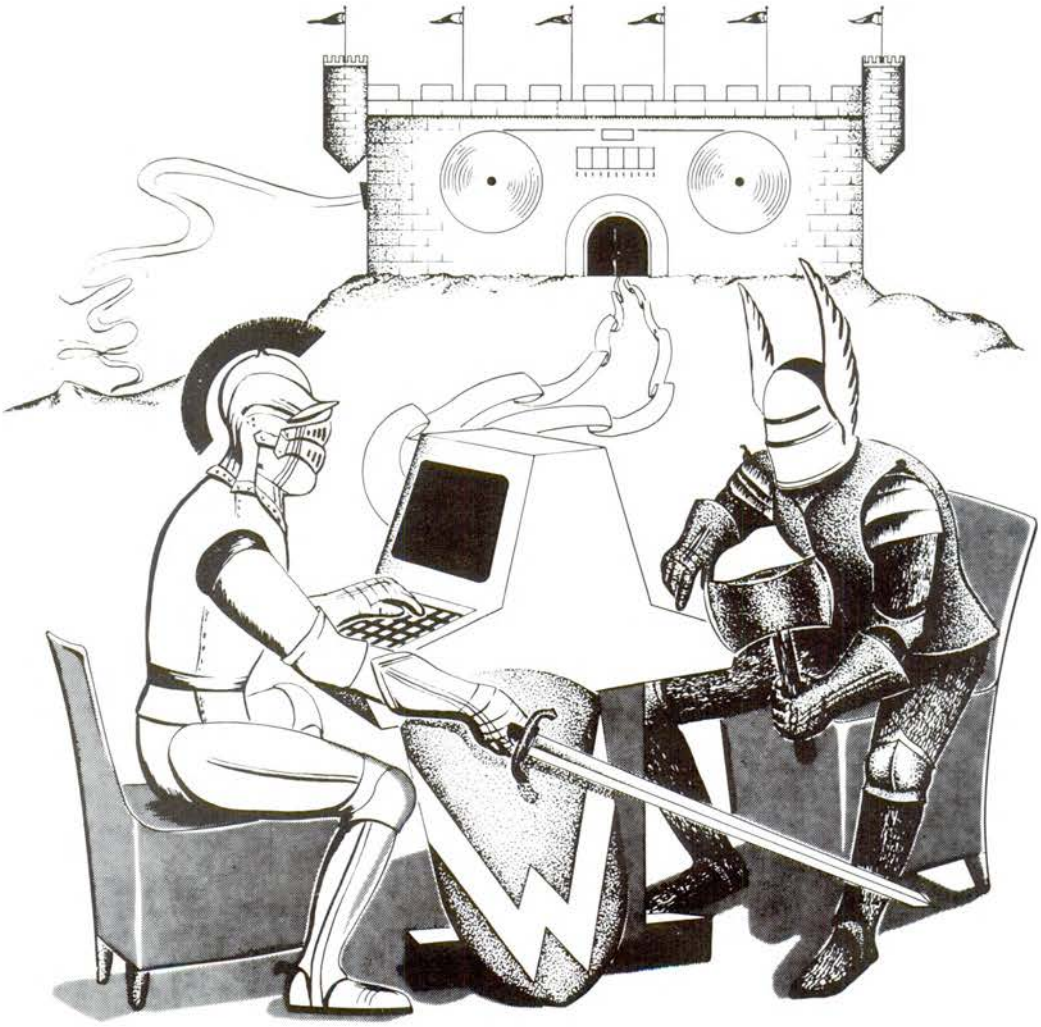
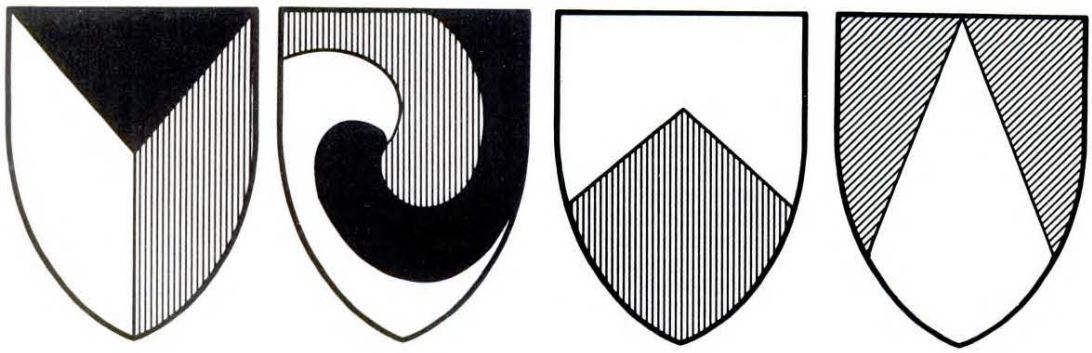
Computer Applications For Crisis Management I&W and Operations Aids

by

Stephen J. Andriole, Judith Ayres Daly and E. Luther Johnson





The Crisis Management Program

The objective of the research on crisis management funded by the Defense Advanced Research Projects Agency's Cybernetics Technology Office (DARPA/CTO) and monitored by the Office of Naval Research (ONR) is to improve command center operations by developing and testing computer-based aids for forecasting, monitoring, and managing crises, as follows:

- Develop and test computer-based early warning and monitoring system(s)
  - Develop multi-track, multi-source indicator systems
  - Develop multi-method forecasting capabilities
  - Develop intra- and international real-time monitoring and forecasting capabilities under the concept of "automated Indications and Warning (I&W)"
  - Develop interactive graphic computer capabilities
- Develop and test computer-based executive decision aids
  - Develop methodologies to anticipate and deal with various types of crises and crisis management problem areas
  - Develop aids to enhance option/action selection during crisis situations
  - Develop methodologies and data sets to gain insight into the processes of "adversary" option/action selection
  - Develop interactive graphic computer capabilities
- Experimentally evaluate, implement, and transfer to operational users new early warning and decision-making aids.

These are exploratory development objectives; they focus on "real-world" operational problems of national security. Such has not always been the case with the Crisis Management Program (CMP). While the dual I&W and crisis decision-making thrusts have been evident

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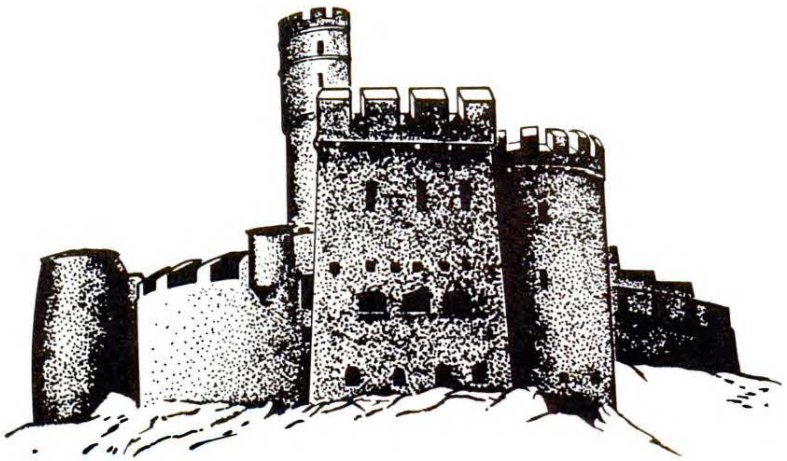
Dr. Daly is currently a Program Manager in the Defense Advanced Research Projects Agency's Defense Sciences Office. Prior to joining DARPA, she was a Project Manager and Research Analyst at Decisions and Designs, Incorporated. She has authored reports and papers in the fields of indicator technology and applied quantitative international relations. Her current research interests include command and control decision as well as forecasting systems. Dr. Daly received her PhD (International Relations, 1976) from Georgetown University and her BA (Political Science, 1968) from Vassar College.

Dr. Johnson, who completed a naval career in 1978, is a specialist in foreign affairs and foreign languages. His field of interest in foreign affairs includes crisis indications and warning. He received a PhD (1966) and an MA (1964) in International Relations from The American University, an MA in Education (1951) and a BA in Romance Languages (1950) from Clark University after attending the University of Lund, Sweden.



since the official inception of the program, methodological (especially technological) evolutions have taken the program much further into the applied area than was initially thought possible.

Crisis Management became an official CTO program in 1973, and early in its history two conferences identified myriad problems in Crisis Management.[1] The problems were broadly defined, encompassing crisis early warning as well as crisis decision-making and ranging from the general to the specific in each area.

It was recognized that both I&W and operations were "high stakes" defense problems. More specific problems and their implications included:

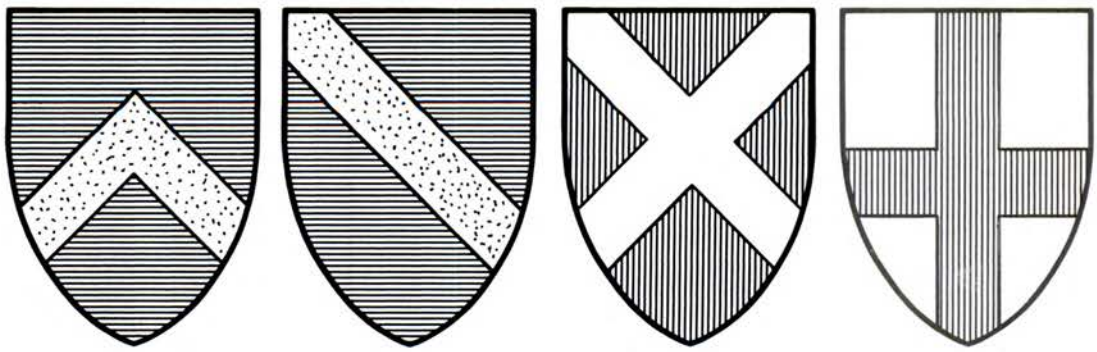
- Procedures
  - Over-reliance on military (and neglect of political and economic) indicators for I&W
  - Short lead time
  - Misses/false alarms
  - Deception
  - Limited option generation and option evaluation in crisis decision-making
- Analyses
  - Traditional approach of intuitive analysis
  - Lack of institutional memory
  - Lack of conceptual/analytical constructs
  - Massive amounts of "non-quantifiable" information
- Information Handling
  - Little use of computer-based methodologies or technologies
  - Manual processing
  - Poor display/dissemination
  - Lack of retrievable historical records

Such procedural, analytical, and information-handling problems contributed to inadequate performance in both I&W and operations. The U.S. intelligence community failed to anticipate over 47% of the intra- and international crises that occurred from 1945 through 1975 (CACI, 1977). The situation was exacerbated by the fact that for the anticipated crises (53% in the 31 year period), the warning time for almost half was seven days or less. Unfortunately, the trend across time exhibited a deterioration of the situation; that is, in terms of accurate crisis warning with long lead time, the performance of the defense and intelligence communities was worse during the 1965-75 period than from 1945-64 (CACI, 1977).

The record is equally unimpressive regarding the management of crises. Contingency plans were inadequate or non-existent for 58% of the crises in the 1945-75 period. Crisis management in this period was also characterized by minimal option/action selection and evaluation. As in crisis warning, management of performance deteriorated over time. This was partly a result of the increasing frequency with which second or third crises developed as offshoots of the primary crisis, apparently placing a great strain upon the defense community's ability to anticipate successfully, avert, or manage intra- and international crises important to U.S. national security.

The DARPA/CTO Crisis Management Program has produced some new solutions to these problems. These solutions have been founded on new analytical constructs and methodologies developed in part by quantitative international relations (IR) scholars; on a slow but perceptible change in the training and skills of members of both the academic and operational communities; and on computer science.

While the I&W and operations thrusts were evident in the early years of the CMP, their focus was fuzzy.



The methodologies used were primarily those of the behavioral and social sciences. While much of the research was computer-based, its products were paper. Data analysis and findings were presented solely in report form, sometimes with a two inch appendix of data print-out or code.

In early 1976, the perspective on the place of computers in CMP research was expanded. They became not merely invisible tools of basic research from which paper products were generated, but vehicles for translating basic research findings into forms understandable by and useful to real-world intelligence analysts and crisis managers on a day-to-day basis. Computers came out of the closet and bridged the gap between basic research, located primarily in the academic community with nebulous notions of the national security problems its efforts could alleviate, and applied work, which while building on excellent basic research, more directly addresses operational I&W and crisis management problems. The expansion of the role of computers in the Crisis Management Program was institutionalized in the Demonstration and Development Facility (DDF). The DDF opened its doors in November 1977 and was designed to support, expedite, and integrate research and applications of the Crisis Management Program.[2] (DDF performance of these functions for the CMP was of such quality that the Facility has recently been expanded to support all other CTO programs.)

The DDF and the change in the role of computers in the CMP that it represents is illustrated in Figure 1 which summarizes the current status of the Program. Basic research continues in several areas, e.g., forecasting and crisis outcome assessment methodologies. However, this basic research is explicitly designed to feed and to be integrated into the user-oriented, interactive computer-based aids representing the two thrusts of the CMP, i.e., the Executive Aids for Crisis Management and the Early Warning and Monitoring System (EWAMS).

The increasing emphasis on applications and transfer is rendered both possible and necessary by the interest of DoD components in actually using CMP products to support their operations. For example, in July 1977 DARPA/CTO signed a Memorandum of Understanding (MOU) with the Defense Intelligence Agency's National Military Indications Center (DIA/NMIC). The MOU has been (and will continue to be) of great benefit to CMP research by allowing input from potential users as to their needs and requirements. CMP research and computer-based products can thus be focused to be more relevant to user needs and to address their problems more directly. DIA/NMIC currently has access to all CMP products via DDF's time-sharing system and all software will shortly be installed on a NMIC computer so that the program can run in parallel with classified systems. Both the Executive Aids and EWAMS are operational at the Naval Postgraduate School and have also been transferred to the CIA's Office of Research and Development. It is probable that CMP products will be transferred to U.S. European Command as well as other commands before the demise of the Program in FY 81.

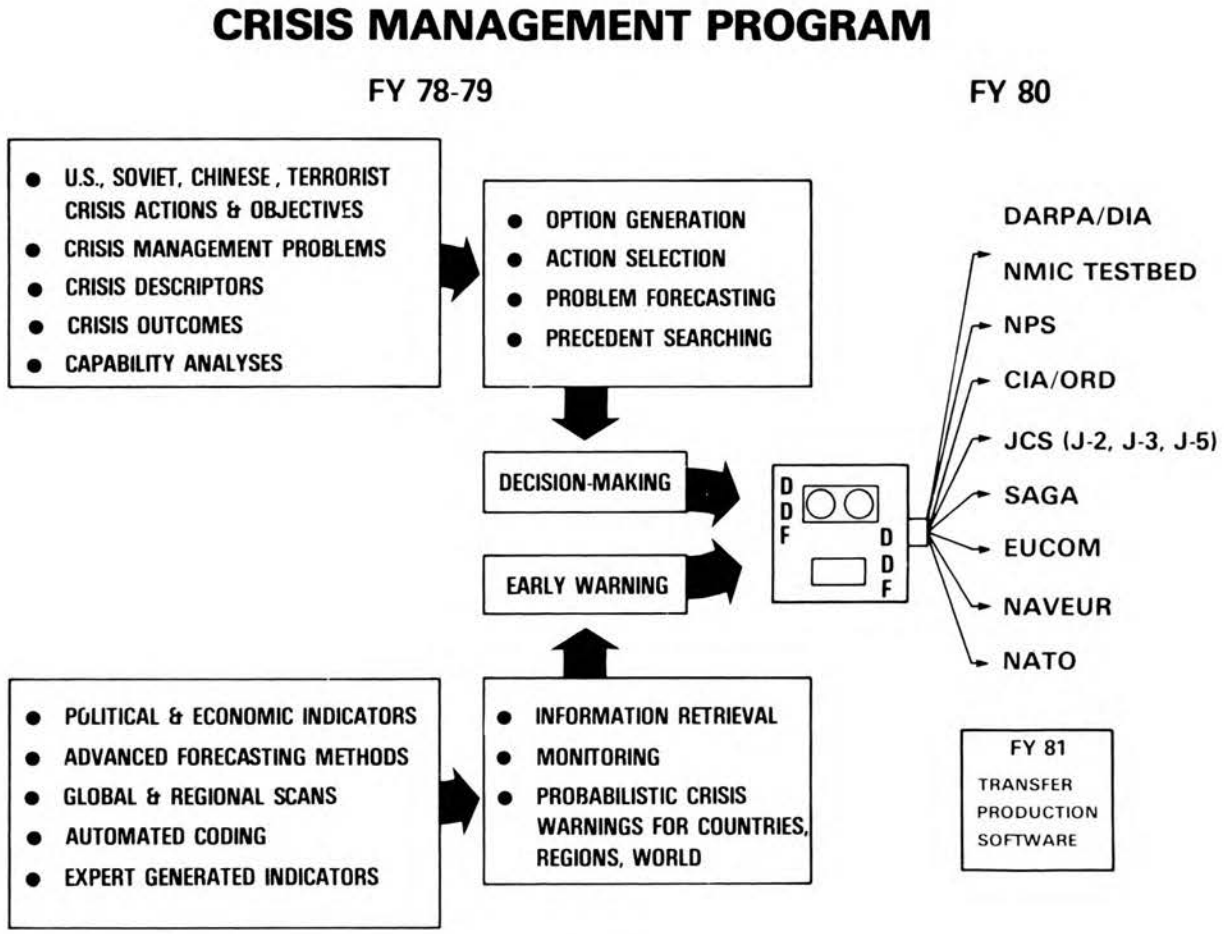


Figure 1

While adaption of CMP methodologies and technologies has been somewhat less than instantaneous and community-wide, there has been recognition that there is an alternative to the "traditional approach of intuitive analysis;" that a never-ending stream of information can be managed with computer-based analytical techniques; that there are alternatives to analyst's "shoeboxes" and that institutional memories can be systematically extended; that even unclassified data, if analyzed with rigorous and systematic methodologies with the speed of computers, can enhance intuitive analyses performed in a classified environment.

The Early Warning and Monitoring System

The Early Warning and Monitoring System (EWAMS) is the lead project on the I&W side of the Crisis Management Program and serves as the vehicle for translating and transferring results of basic research in diverse areas to the user community. The EWAMS is being developed to alleviate a variety of problems in the I&W process. Among these are: (1) heavy reliance on the use of qualitative methods to generate estimates. (Such methods depend on judgment, intuition, experience, and memory of the analyst); (2) manual processing and analysis; (3) relative neglect of political and economic indicators in favor of military ones; and (4) forecasting methods that rarely take advantage of developments in the social, behavioral, and computer sciences. While Figure 2 presents the current configuration of EWAMS, its key components can be discussed in terms of quantitative political indicators, a monitoring and short-range forecasting capability, and a computer-base.

The foundation of the EWAMS indicators is the World Event Interaction Survey (WEIS) coding scheme which converts "soft," narrative information about international political affairs into hard, quantitative data. This has been accomplished despite the assumption that political information, unlike military informa-

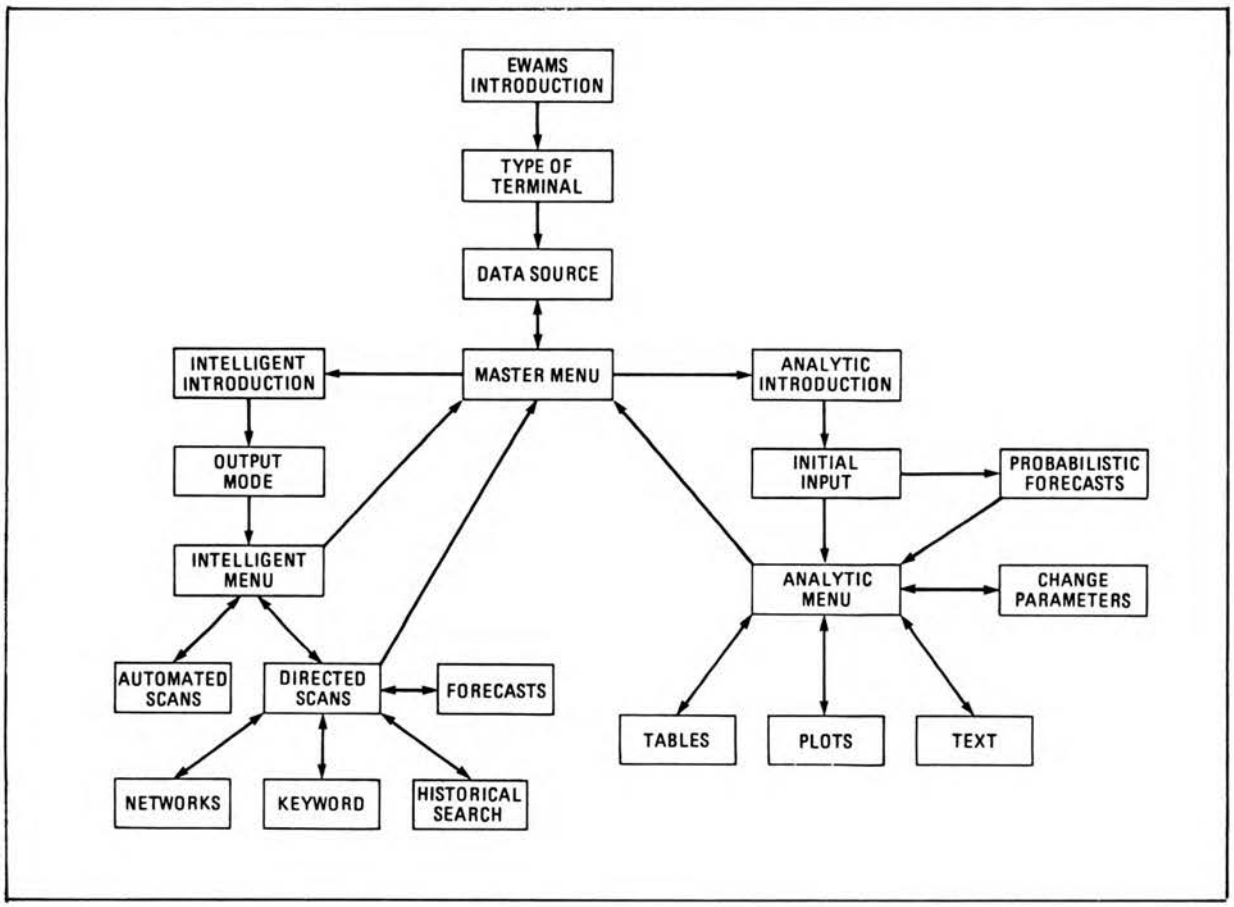


Figure 2. The Early Warning and Monitoring System: an Overview

tion, was too subtle and deceptive to be converted to useful quantitative indicators. As illustrated in Figure 3 the WEIS coding scheme contains 62 distinct kinds of international political events that can be aggregated into 22 major categories, 10 of which are cooperative and 12 of which are conflictual.

The coding scheme has been used to generate several international political data bases including a very large one from the *New York Times*. Each of the 110,000 events in this data base consists of information on who did what to whom, i.e., what country acted in a certain way toward what other country. Each of the event coding elements (initiator, event type, recipient, and date) have numeric equivalents and are stored digitally on tape or disc. The three data bases for EWAMS and their beginning dates are the *New York Times* (1966), *Times of London/Manchester Guardian* (1978), and The Foreign Broadcast Information Service's *Daily Report* for selected areas (1979).

From these data bases, researchers have developed quantitative indicators of international political behavior. The five key ones in the current EWAMS are:

- The total of all political event types sent or exchanged by a pair of countries;
- The aggregate of cooperative political events sent or exchanged;
- The total of conflictual political events sent or exchanged;
- Political tension, whose algorithm is:

$$\text{tension} = \frac{\text{conflictual events}}{\text{total events}} \left[1 - \frac{1}{\text{total events}}\right] 100$$

For example, 20 conflictual events of a total of 70 would be computed as follows:

$$\text{tension} = \frac{20}{70}\left[1 - \frac{1}{70}\right]100$$

$$= 0.2857(0.9857)(100) = 28.16$$

COOPERATIVE EVENTS

1. Yield
   - 011 Surrender, yield to order, submit to arrest, etc.
   - 012 Yield position, retreat, evacuate
   - 013 Admit wrongdoing, retract statement
2. Comment
   - 021 Explicit decline to comment
   - 022 Comment on situation-pessimistic
   - 023 Comment on situation-neutral
   - 024 Comment on situation-optimistic
   - 025 Explain policy or future position
3. Consult
   - 031 Meet with, at a neutral site, or send note
   - 032 Visit, go to
   - 033 Receive visit, host
4. Approve
   - 041 Praise, hail, applaud, condolences
   - 042 Endorse other policy or position, give verbal support
5. Promise
   - 051 Promise own policy support
   - 052 Promise material support
   - 053 Promise other future support
   - 054 Assure, reassure
6. Grant
   - 061 Express regret, apologize
   - 062 Give state invitation
   - 063 Grant asylum
   - 064 Grant privilege, diplomatic recognition de facto relations, etc.
   - 065 Suspend negative sanctions, truce
   - 066 Release and/or return persons or property
7. Reward
   - 071 Extend economic aid
   - 072 Extend military assistance
   - 073 Give other assistance
8. Agree
   - 081 Make substantive agreement
   - 082 Agree to future action or procedure, agree to meet, to negotiate
9. Request
   - 091 Ask for information
   - 092 Ask for policy assistance
   - 093 Ask for material assistance
   - 094 Request action, call for
   - 095 Entreat, plead, appeal to
10. Propose
    - 101 Offer proposal
    - 102 Urge or suggest action or policy

CONFLICTUAL EVENTS

11. Reject
    - 111 Turn down proposal, reject protest demand, threat, etc.
    - 112 Refuse, oppose, refuse to allow
12. Accuse
    - 121 Charge, criticize, blame, disapprove
    - 122 Denounce, denigrate, abuse
13. Protest
    - 131 Make complaint (not formal)
    - 132 Formal complaint or protest
14. Deny
    - 141 Deny an accusation
    - 142 Deny an attributed policy, action, role or position
15. Demand
    - 150 Issue order or command, insist, demand compliance, etc.
16. Warn
    - 160 Give warning
17. Threaten
    - 171 Threat without specific negative sanctions
    - 172 Threat with specific negative sanctions
    - 173 Threat with force specified
    - 174 Ultimatum, threat with time limit and negative sanctions specified
18. Demonstrate
    - 181 Nonmilitary demonstration, walk-out on
    - 182 Armed force mobilization, exercise and/or display
19. Reduce Relationship
    - 191 Cancel or postpone event
    - 192 Reduce routine international activity, recall officials, etc.
    - 194 Halt negotiations
    - 195 Break diplomatic relations
20. Expel
    - 201 Order personnel out of country
    - 202 Expel organization or group
21. Seize
    - 211 Seize position or possessions
    - 212 Detain or arrest person(s)
22. Force
    - 221 Non-injury destructive act
    - 222 Nonmilitary injury/desctruction
    - 223 Military engagement

THE WEIS EVENTS CODING SCHEME

Figure 3

- Political uncertainty, which is a measure of the range or variety of events exchanged across the twenty-two event categories; uncertainty ranges from 0 to 1 with the former indicating consistent behavior (low uncertainty) and the latter inconsistent behavior (high uncertainty).

The EWAMS enables the analyst to monitor international political activity with the raw values of these indicators or with the deviations from their normal behavior. These deviations, or z-scores, represent the number of standard deviations from computed means of political activity, tension, and uncertainty for the pair of countries being examined. This methodology enables the analyst to track the political relations between any two countries and to isolate those country pairs exhibiting deviations from empirically established norms.

These measures of abnormality are used to generate short-range forecasts. More specifically, when the user examines a country pair, the computer correlates the z-scores for the indicators with those in the crisis, pre-crisis, and non-crisis periods for many historical crises. For example, when a z-score of +10 is observed the computer searches through the entire international event data base, locates the historical reference cases, and matches the observed score with those generated by the reference cases. The crisis probabilities reflect the percentage of times the observed current scores match those occurring in the past. For instance, if an analysis of past events reveals that 75 percent of historical crises occurred within thirty days when z-scores of conflict activity range from +8 to +11, then the observation of similar current scores would be accompanied by a crisis probability of .75.

The entire system (event data, indicators, and monitoring and forecasting methodology) runs on a PDP 11/70 minicomputer and is accessed via Tektronix graphic terminals. To meet the requirements of some operational users, EWAMS is being converted from FORTRAN IV to BASIC to run on the Tektronix 4051 microprocessor with triple diskettes. Both computer configurations include hard-copy units that enable users to generate high-quality paper copies of whatever appears on the graphic terminal screens.

The two very different ways of using EWAMS are labelled Automated I&W and Analytic EWAMS. The former is the more recent capability and is intended to make the analyst more efficient by automating several of his standard tasks, focusing his attention and supplementing his other sources of information. In Figure 4 the analyst has accessed the Automated rather than the Analytic I&W module, chosen the *New York Times* data base, and the hotspots option for the first six months of 1979.

The system then goes out and calculates the conflict events output by all countries and international organizations in the world for the period the user has specified. It selects the top ten in terms of conflict frequency and produces the output shown in Figure 4. The user then narrows his focus to the month of July 1979 and gets the output shown in Figure 5. Israel has replaced the USA as Number 1 and the PLO (Palestine Liberation Organization) has moved up on the hotspot list. The hotspot list is one of the features of the automated I&W component of EWAMS that can make the analyst more efficient. For example, if the user accesses this feature first thing in the morning and finds that nothing has changed since the previous day or there are no countries on the hotspot list which are of concern to him, he can concentrate on other matters

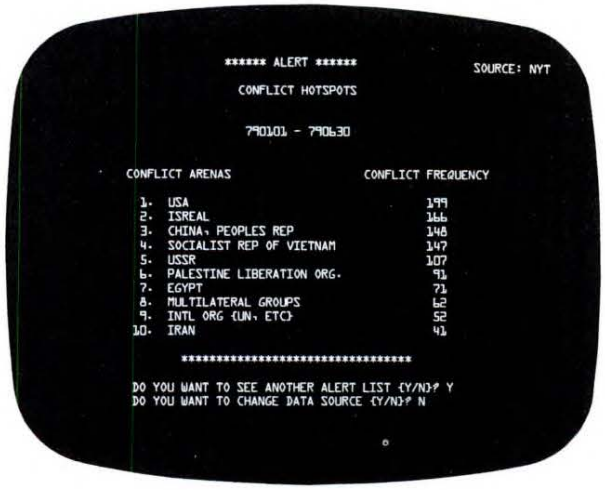


Figure 4

Figure 5

Figure 6

during his watch. If, however, there has been a change or a country that falls under his purview appears on the list, he can exercise other options of EWAMS to obtain more detail on the reasons for the country or countries' appearance on the hotspot list.

Automated I&W also includes warning and monitoring alert lists.[3] When the user requests an alert list the system first calculates a hotspot list for the three months prior to the date input by the analyst, the date for which he wants a forecast. In this case the input date is 1 August; therefore, using the *Manchester Guardian* data base the system calculates a hotspot list for May, June, and July. The impact of the switch from the *New York Times* to the *Manchester Guardian* can be seen by the appearance of the United Kingdom, the United Arab Republic and Iran on the list. The user can easily change this list before it is used to calculate the monitoring and warning list. (This interactive add-delete process is not included in the sample output.) As illustrated in Figure 6, the user deletes the United Kingdom and Rhodesia. There are thus 8 countries on the list to be used in the calculation of the monitoring and warning alert list. The computer then calculates the indicators for every possible country pair on the list (in this case 28 country pairs). After calculating all the indicators, the system searches for those indicator readings which are at or above a pre-set threshold. Nine country pairs satisfy the criterion and are output for the user (Figure 7). For warning alert lists, the system goes through the same process; however, the pre-set thresholds are higher than for the monitoring alert list. In this case, only the Israeli-PLO country pair meets or passes the threshold (Figure 8). Like the conflict hotspots, the monitoring and warning alert lists are intended to make analysts more efficient and to focus their attention.

Figure 7

Figure 8

However, the methodology for doing this is different and provides the analyst with more information since he knows that the lists are based on pre-set thresholds for the EWAMS indicators. If the analyst wishes to know how the indicators are performing for a given country pair, he can move over to the analytic side of EWAMS. This is illustrated in the next set of output.

Analytic EWAMS provides the user with a very flexible set of inputs by which he can specify the countries (or regions), the direction of international political activity, the time aggregations (daily, weekly, monthly, quarterly, or annually), and the time periods he wants to examine. Figure 9 illustrates these options for Uganda-Tanzania on a daily basis beginning on 1 October 1978.[4] This system outputs a graph (see Figure 10) showing the trend in conflictual activity with standardized or z-scored data so that the graphical representation depicts a pattern which is relative to past Uganda-Tanzania activity. There are three distinct peaks, each higher than its predecessor. The process by which the user can easily change his input options is not shown here; however, Figure 11 shows the total, cooperative, and conflictual political activity indicators in the raw, not standardized form. The graphical display depicts a relationship which is hostile or conflictual in tone throughout October and November 1978. As shown in Tables 1 and 2 the analyst can also request tabular output for the indicators. For the same two countries during the 8-week period, total activity fluctuated considerably and tension scores were unusually high (above 50.0 for 6 of the 8 weeks and above 70.0 during two weeks). Uncertainty peaked at .58 during the week of 29 October.

If the user wants more substantive detail on indicator performance, he can easily retrieve brief textual descriptions of the actual events that are aggregated into the indicators. To do this the user needs only to specify the event types and the system responds with the requested text. In addition the system has a key-

Figure 9

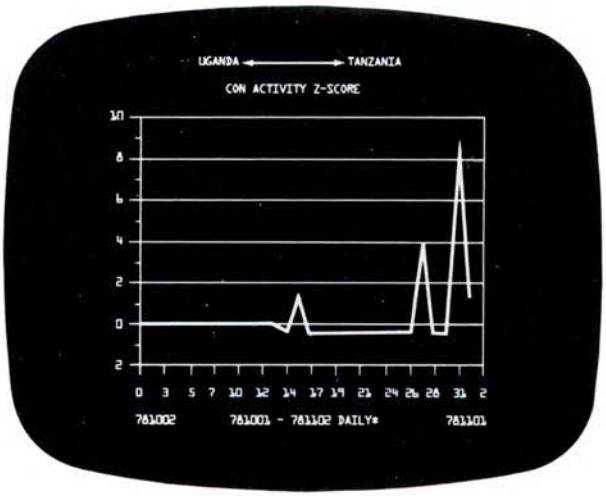


Figure 10

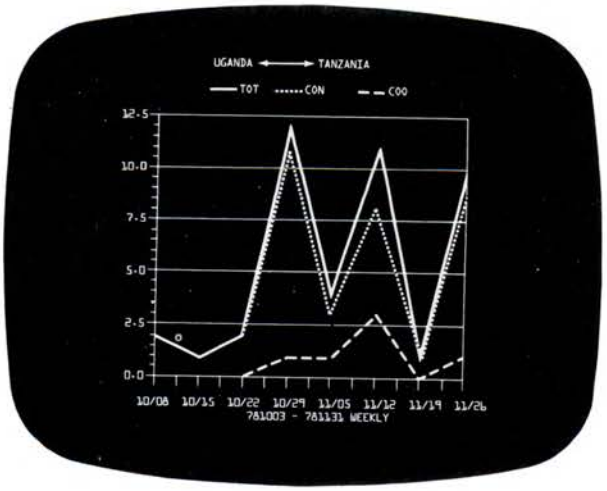


Figure 11

SOURCE: MAG

WEEKLY ACTIVITY
781003 - 781131

*** UGA <<<<< TWO-WAY FLOW >>>>> TAZ ***

	TOTAL ACTIVITY		COOPERATIVE ACTIVITY		CONFLICTUAL ACTIVITY	
DATE	NUMBER	Z-SCORE	NUMBER	Z-SCORE	NUMBER	Z-SCORE
781008	2	0.00	0	0.00	2	0.00
781015	1	0.82	0	0.00	1	0.82
781022	2	2.00	0	0.00	2	2.00
781029	12	12.42	1	0.00	11	11.32
781105	4	0.54	1	2.67	3	0.34
781112	11	2.39	3	6.64	8	1.80
781119	1	-0.43	0	-0.49	1	-0.39
781126	10	1.78	1	0.65	9	1.88

SOURCE: MAG

WEEKLY TENSION AND UNCERTAINTY
781003 - 781131

*** UGA <<<<< TWO-WAY FLOW >>>>> TAZ ***

DATE	TENSION	Z-SCORE	H-REL	Z-SCORE
781008	50.0	0.00	0.224	0.00
781015	28.0	0.96	0.000	-0.41
781022	50.0	1.94	0.224	2.27
781029	84.0	2.94	0.580	5.04
781105	65.3	1.04	0.336	1.11
781112	66.1	1.26	0.541	2.01
781119	28.0	-0.00	0.000	-0.77
781126	81.0	1.67	0.476	1.43

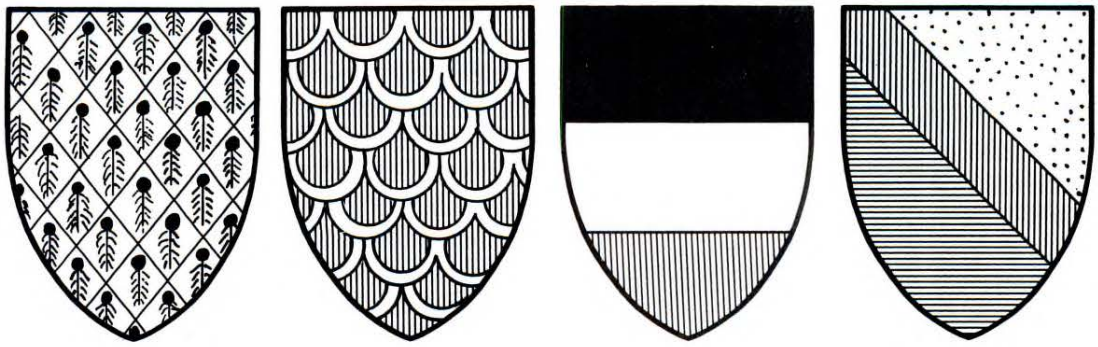
Tables I and II

word search routine that allows rapid search of more than 120,000 international political events exchanged among all countries in the world from 1966 to the present. It can be used to retrieve all text containing any combination of keywords, e.g., SALT and Cruise Missiles.

Of the many coming improvements to EWAMS, two are highly relevant to readers of the *ONR Research Reviews,* particularly those attached to larger staffs. The first concerns possible integration of the political indicator system with existing computer-based military indicator systems of similar design. This will allow examination of the contention that political indicators are likely to precede military ones, and thus increase the time to analyze and prepare for important international events and crises. The second enhancement concerns further development of the automated I&W component of the system. For example, in addition to the present capabilities, threat-spreading networks will be generated, e.g., a North Korean and South Korean tension level of .80 would automatically trigger an examination of relations between the U.S. and South Korea and the USSR and North Korea. Work on computer-based systems such as the one described here is aimed at modernizing the processes by which the Department of Defense conducts much of its business. Modernizing the Indications and Warning process is particularly important, given the improved state-of-the-art and the rather poor 30-year track record. Yet, such systems cannot and should not eliminate human judgments. Experienced evaluation of statistical data is essential to the warning process. The computer makes statistical data more easily accessible to the analyst and provides a flexible means of analyzing and displaying information relevant to national security, as an aid to conceptualization and interpretation. The executive aids for crisis management, to which we now turn, can also offer such assistance.

The Executive Aids for Crisis Management

The Executive Aids constitute the lead project on the operations side of the Crisis Management Program. They are addressed to the problems of lack of institutional memory and information overload as well as inability to access information and to the need for precedents to guide option selection. The aids are designed to answer command and operational staff questions such as "What has been done in previous crises of this type?" "With what success?" "What problems are likely to be encountered in this crisis?" The interactive computer-based aids offer a partial solution to such problems by allowing rapid identification and examination of crisis precedents, actions, outcomes, and problems.



These capabilities are founded on the aid's data bases that consist of the actions, objectives, problems encountered, and characteristics of crisis in which the U.S., Soviets, or Chinese were involved since World War II.[5] The respective numbers of cases are currently 324; 386; and 386. While Figures 12 through 14 are focused on the three components of the U.S. aid, parallel systems exist for the Soviets and Chinese. The aids run on both a portable desk-type Tektronix 4051 with graphics display and a PDP 11/70 minicomputer. The output in Figures 15 and 16 is taken directly from the terminal screen. The Angola output illustrates how the aids can assist crisis managers under severe time pressure in generation of action alternatives, analysis of crisis precedents and suggestion of Command objectives. The existence of the Soviet and Chinese aids, not shown here, permit ready comparison with U.S. perspectives.

While the aids enable crisis managers to sort, assemble, and analyze data very rapidly and in preliminary performance tests have increased the range of option generation and evaluation by nearly 100% and reduced precedent search time by at least 50%, they are still essentially descriptive. However, ongoing research in two areas promises to enhance their prescriptive nature.

The first is a Problem Forecaster aimed at assisting operators in anticipating problems to be encountered in a crisis. Founded on the problem sections of the three superpower crisis data bases, research is on-going to: (1) forecast problem occurrences from categories of crises; (2) help the operator anticipate problems likely to arise on, e.g., day 15 of a crisis given its characteristics earlier in the conflict.[6]

The second focuses on one of the most important aspects of crisis management that has, heretofore, seen relatively little research – the assessment of crisis outcomes. This research area is characterized by analytical questions that are much more difficult than those encountered in examining characteristics of crises and the actions, objectives, and problems encountered in the process of crisis management. The objective and systematic assessment of crisis outcomes permits moving beyond descriptive analyses of crisis actions to determine what types of actions are more or less effective in particular types of crises situations.

Actions/Objectives Crisis Management Decision Aid

This section is designed to assist Department of Defense personnel in evaluating proposed courses of action and sets of U.S. Objectives based on data from 101 crises involving the United States between 1956-1976.

The user is given three levels of analytic assistance:

1. The capacity to search for historical cases with sets of user-specified U.S. actions or objectives.

2. The capacity to identify, across all cases, those actions that have historically been most strongly associated with each objective selected by the program-user;

3. The capacity to identify, across all cases, those actions that have historically been most commonly associated with sets of U.S. objectives selected by the program-user.

Would you like to see a summary of another system section?

Press 'Y' or 'N' and 'Return'.

Y

Enter 'I', 'II', or 'III'.

II

Figure 12

Crisis Management Problem Analyzer

This section permits a detailed examination of management problems encountered in 41 selected cases (1956-1976).

Major problem categories are:

1. System-related delays in decision-making
2. System/procedural constraints on actions
3. Legal issues involved
4. Resources inadequate for decision-making/ action
5. Intelligence failures at decision-making level
6. Emotion/ideological issues involved in decisions
7. Interpersonal factors in decision-making
8. Prolonged crisis problems
9. Problems in selecting action personnel
10. Constraints on operations
11. Physiological problems for operating forces
12. Information failures by operating forces
13. Failures in taking appropriate/timely action
14. Forstat problems
15. Problems in the operating environment
16. General problems in crisis planning
17. General problems in crisis handling
18. General problems in crisis timing

Would you like to see a summary of another system section?

Press 'Y' or 'N' and 'Return'.

Y

Enter 'I', 'I', or 'III'.

III

Figure 13

Crisis Descriptor

This section provides access to information on 307 crises (1946-1976). The data may be searched for cases matching the user's specifications, or a full description may be printed for any selected case.

Categories of information coded for each crisis are:

- Year and brief description
- Location of crisis
- Nature or pre-crisis activity
- Duration of pre-crisis period
- Scope of crisis (domestic or international)
- Nature of crisis (military, political, both)
- Crisis duration
- Timing of crisis resolution
- Crisis outcome
- Anticipation of crisis
- Degree of threat to U.S. interests
- Timing of threat development
- Time available for decision
- Sizes of participants/degree of U.S. interests
- U.S. response/participation
- U.S. objectives
- Nuclear/non-nuclear implications

Would you like to see a summary of another system section?

Press 'Y' or 'N' and 'Return'.

N

Figure 14

The technical approach being followed in this ongoing research consists of the following:[7]

- The articulation of a set of goals or objectives for the Soviets and the U.S.
- The identification of crisis outcomes and the development of methodologies to measure them
- Specification of the time periods to be used to deal with short-term (immediate crisis aftermath) and longer-term consequences of the crises
- Development of operational criteria for the comparison of goals and outcomes, to assess the extent to which the Soviets and the U.S.

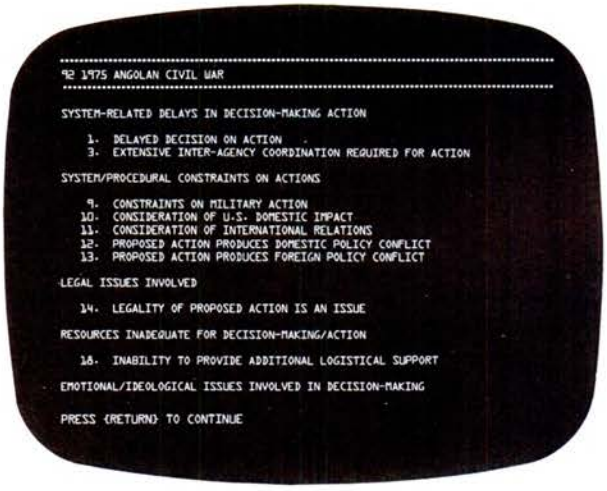


Figure 15

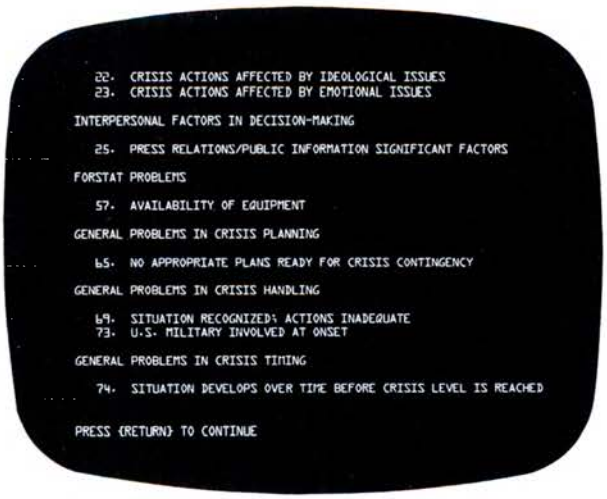


Figure 16

achieve their goals (both long-term and short-term) after the crisis

At the conclusion of the research, there will be a quantified data base for the outcomes of Soviet and U.S. crises which occurred between 1966 and 1978. This data base will permit several kinds of analyses that are not now possible, to include:[7]

- Comparative analyses of Soviet and U.S. crisis performance (i.e., the relative extent to which each superpower achieved certain types of goals during the period surveyed)
- Identification of the type of outcome (for each superpower) that are most or least often achieved
- Assessments of the relative efficacy of actions and combinations of actions .

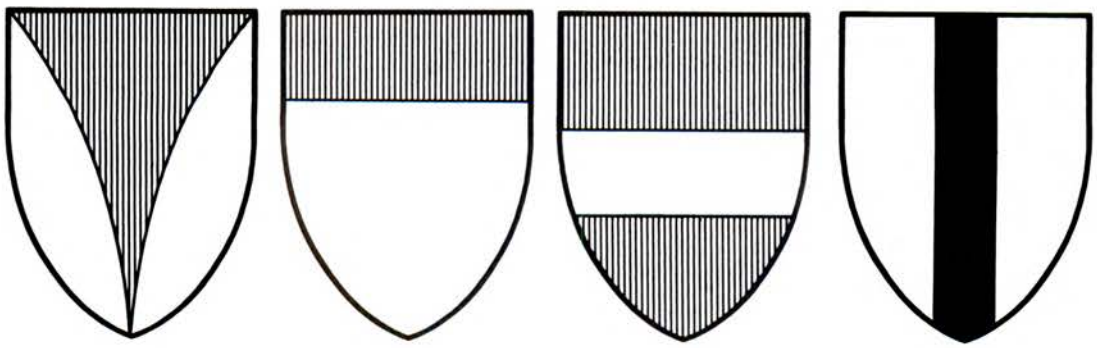
Future Crisis Management Research

While EWAMS and the Executive Aids have demonstrated the utility to DoD of a marriage of computers and basic quantitative social science research, there is much yet to be done – and the revolution in computer science will determine the offspring of the merger. While some of the following brief discussion of the future of crisis management research may seem bizarre, it focuses merely on the near-term and eminently feasible.[8]

On *today's* drawing boards is a whole new set of ideas designed to make the crisis manager more efficient than he is now. Some of these ideas include teleconferencing, spatial data management, computerized inference-making via new advances in artificial intelligence, computerized group decision-making, and "intelligent" monitoring and warning systems.

While teleconferencing is not new, it has yet to be perfected into actual use. Within the next decade, however, we can expect decisions to be teleconferenced routinely. Communications will permit instant visual and audio contact. Computer programs will instantaneously translate even the most bizarre languages, and gestures and nuances will also be immediately interpreted and communicated. The applications will range from within-group consultation to high-level international negotiations. Individuals and groups will teleconference within the teleconferences and command computer slaves to provide them with information and even judgments.

When individuals attempt to retrieve or manipulate information (data, to the researcher) they will not use a conventional alphanumeric keyboard. They will instead enter their own personalized electronic work spaces. These work spaces will display information in

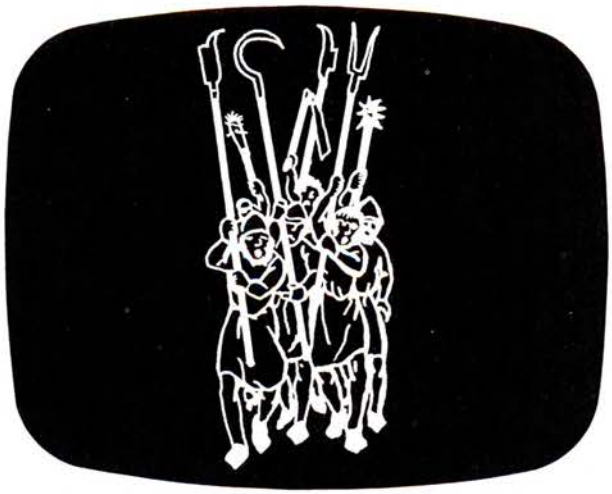


a variety of forms. They will talk to the user and help him to get what he wants. The user, in turn, will talk with the information and direct its activities. While all of this may sound unbelievable, a prototype SDMS (Spatial Data Management System) is now operational at the Massachusetts Institute of Technology.

Such management systems will have unique capabilities. They will not only be capable of graphic data retrieval and manipulation, but will also perform "intelligent" tasks. They will be able to discuss philosophy, to reason, and to entertain. They will be excellent inference drawers. From abstract or substantive knowledge bases, they will be able to interpret events for us and recommend courses of action. They will understand what they hear and read (at inhuman rates of speed), reason clearly, and assume various decision-making roles.

Groups no longer labor over (crisis) management decision-making issues irrelevant to the group's preferred decision outcome. Members of the group who disagree will be invited to discuss the disagreement without disrupting the rest of the group and profiles of "conservative," "stubborn," and "free-wheeling" decision-makers will be quickly and routinely drawn. Decision-makers will thus know to whom to give power and who to avoid. Efficiency should increase by orders of magnitude.

Decision-makers will also rely upon "intelligent" monitoring and warning systems based on the primitive automated one discussed above. Such systems will automatically and incessantly monitor all of the interactions among all of the world's actors. Economic activity will be tracked and correlated with political, military, social, religious, and cultural activity. Searches will occur automatically as will other intelligent systems. International threats will be monitored routinely and threat networks developed before and as danger approaches. The management system will then be activated and, hopefully, crises will be averted. ■



Footnotes

[1] See DARPA/Human Resources Research Office (1973) and DARPA/Cybernetics Technology Office (1976).

[2] For elaboration on this see Andriole, Daly, and Wittmeyer (1978).

[3] For details on the methodology underlying alert lists, see Rossa (1979) and Hopple, Rossa, and Bell (1979).

[4] This section borrows heavily from International Public Policy Research Corporation (1979).

[5] For more detail on the Executive Aids, see CACI, Inc. (1979).

[6] For details see CACI (1978).

[7] This borrows heavily from and is elaborated on in Mahoney (1978).

[8] For a discussion of more futuristic research, see Andriole (1978).

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profiles in science

Captain C. Robert Valeri, MC, USN, is director of the Naval Blood Research Laboratory, Boston, Massachusetts, which post he assumed in 1963. Under Dr. Valeri's direction, the Laboratory has been responsible for some of the most important work done in the field of long-term preservation of the cellular components of blood and

related aspects of medicine. The Laboratory was established in 1956 as a naval facility supported by the Navy Bureau of Medicine and Surgery (See page 20). Since 1978, the Laboratory has been administered by Boston University under an Office of Naval Research contract.

Dr. Valeri's major scientific contributions include:

- Establishing the importance of oxygen transport function of preserved red blood cells in the treatment of patients with fixed coronary and cerebral blood flow, hypothermic patients in hemorrhagic shock, and patients undergoing cardiopulmonary bypass
- Salvaging of outdated O-positive and O-negative red blood cells by biochemical treatment prior to freezing
- Biochemical treatment of red blood cells in order to improve oxygen transport function after transfusion into patients with normal body temperature
- Biochemical treatment of red blood cells to prepare them for improved oxygen transport function after transfusion into hypothermic patients undergoing cardiopulmonary bypass and hypothermic patients in hemorrhagic shock
- Establishing the importance of preserved human platelets that function immediately following transfusion to restore or maintain hemostatsis
- Recognizing the disease state associated with traumatic injuries, "missing blood syndrome," and then developing a successful treatment for the condition.

Dr. Valeri is the author of more than 200 scientific publications including the book *Blood Banking and the Use of Frozen Blood Products.* Another book, *Hypovolemic Anemia of Trauma,* will be published soon. He is a member of the National Research Council Ad Hoc Committee on Red Blood Cell Preservation and a consultant to the National Institute of Health. ■

Naval Laboratory: Leader in FROZEN BLOOD

by

Mark D. Altschule
Office of Naval Research
Boston Branch

The original Chelsea Naval Hospital as it was a hundred and twenty-five years ago. This building remained in use as a female dormitory until the Chelsea Naval Hospital was disestablished. It still stands.

World War II was the first conflict in which technological advances developed by non-military establishments were used on a large scale in response to military requirements. This was true in many fields, but especially so in medicine. Boston University's position among the leaders in medical research had almost immediate effects, although regrettably not all of them were good at first. The scientific community had yet to learn (and still has) that scientific theory may be a poor guide to medical practice. On the one hand, the accomplishments of the National Academy of Sciences/National Research Council in furthering the conquest of infectious diseases by making available antibiotics, antimalarials, and pesticides were notably successful. On the other hand, some of the Council's efforts in other directions were not, and one of these involved the Boston academic medical community.

As America's entry in World War II became increasingly likely, the National Research Council (NRC) interested itself in the problem of shock caused by trauma, hemorrhage, and burns. Unfortunately, their conception was based on fragmentary data from inadequate observations carried out decades earlier. The NRC Committee on Transfusion declared that the main disorder of trauma was a loss of fluid from the blood vessels, with the result that the blood was decreased in volume and increased in viscosity. The treatment recommended was to give blood plasma into a vein. These unsubstantiated conclusions were presented in a manual distributed under the direction of the Committee on Surgery of the Council's Division of Medical Sciences. In the meantime Edwin J. Cohn of Harvard University had been studying the proteins of the blood plasma and had developed methods of separating and purifying them without damage. In response to a request of the NRC, he began a program in 1940 that led to development of large-scale methods of separating blood plasma and its proteins, both in solution and in dry form, from human whole blood. From August 1941 to June 1946 this work was supported by the Office of Scientific Research and Development (the parent Organization of ONR). Cohn's contract gave him the responsibility for making chemical studies of the processes and products, which he did with colleagues and some contractors. Cohn was also charged with making clinical studies, but since he was not a physician and could not identify physicians who could properly conduct necessary studies, the clinical observations were not made.

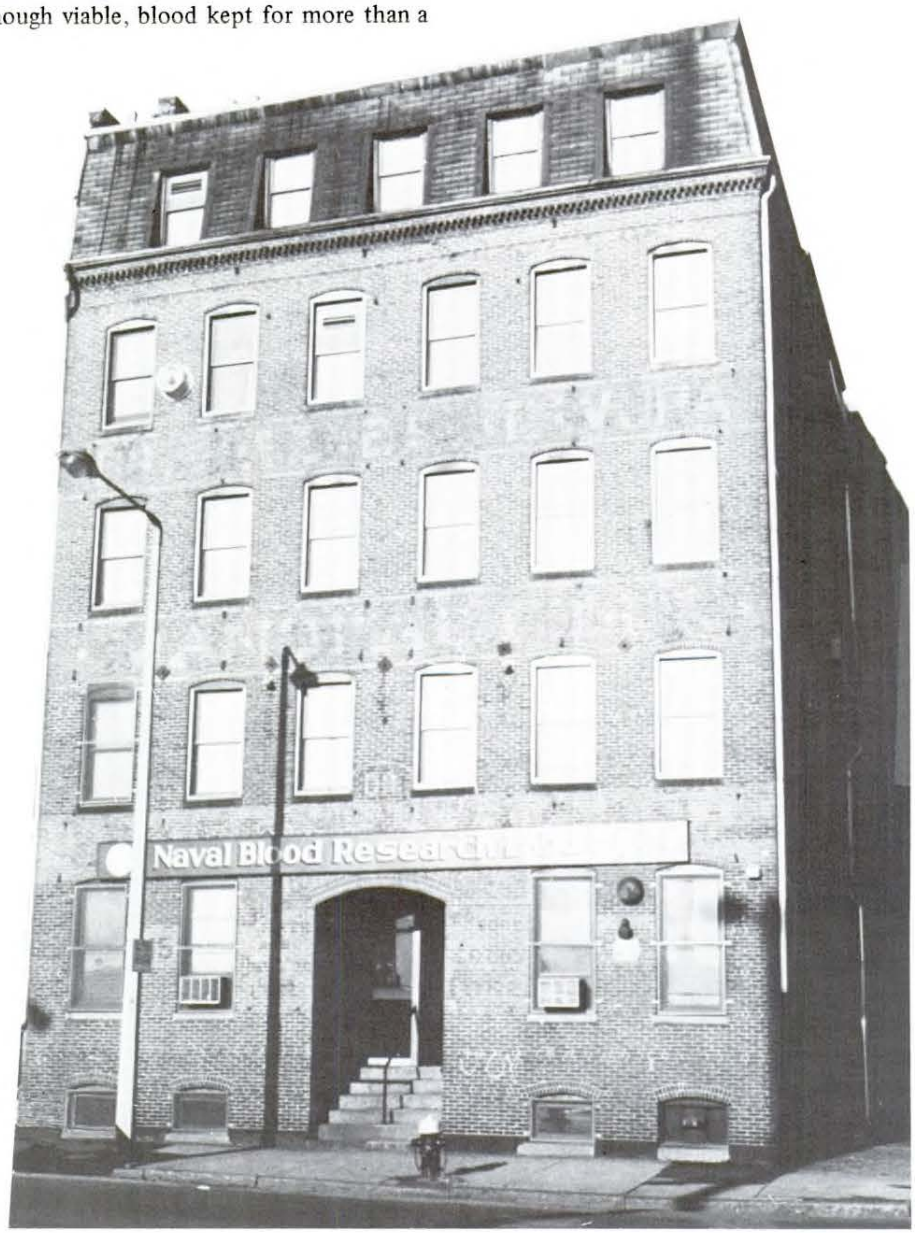
Dr. Altschule is emeritus clinical professor of medicine at Harvard and former lecturer in medicine at Yale University and at Boston University. Although the author of several hundred papers on the physiology and chemistry of disease and of stress, his main interest is the complex interrelations among bedside medicine, laboratory science, and the social milieu in which they both function simultaneously. He currently is on the staff of the ONR Branch Office, Boston, working on the biochemistry of stress, of aging, and of alcoholism, as well as a number of historical projects.

As a consequence, the U.S. Fifth Army entered the North African campaign in 1942 with large amounts of plasma and absolutely no facilities for blood transfusion. (The British Army had extensive facilities for taking and administering blood.) Another Harvard Medical professor, Edward D. Churchill, a surgeon with the Fifth Army, soon recognized and stated the adverse effects of using plasma when whole blood was necessary. There is no way of knowing how many American wounded died as a result of this example of inadequate evaluation for clinical use of an important scientific discovery.

Cohn's group derived a number of protein products from blood plasma that were very useful over a period of years in a variety of medical conditions. For example, purified plasma albumin became available for treatment of diseases that caused serious losses of albumin from the body. Another product was gamma globulin, a mixture containing substances that induced a temporary state of immunity to a number of infectious diseases and might, therefore, be used to prevent the development

of these diseases (e.g., hepatitis) in persons who were exposed to them. Nevertheless, the goal of developing a blood preparation or product that would specifically counteract the effects of severe hemorrhagic shock had eluded the investigators. The experience in combat had shown quite clearly that, although plasma was often useful in the immediate resuscitation of the wounded, the specific effective treatment was the giving of red blood cells. However, blood collected for future use could be preserved only about three weeks. (We now know that, although viable, blood kept for more than a week does not provide optimal function, but that is another story.)

At the end of World War II, Cohn created the Protein Foundation, a non-profit organization, supported by his patents and other funds, in the continuing study of the preparation, properties, and uses of the blood proteins. However, the lessons clearly learned in combat – that the definitive treatment of shock due to hemorrhage was to give not plasma but red blood



The new Naval Blood Research Laboratory, Boston, operates in this building donated by the New England Nuclear Corporation. It is adjacent to the Boston University School of Medicine on Albany Street.

cells – was not forgotten. A number of investigators, including Cohn's group, applied themselves to the problem of preparing red blood cells for prolonged preservation without causing functional deterioration. A proposed solution of the problem was to freeze the red blood cells, but this could be done only after separating them from the blood plasma. Cohn's group developed a high-technology kind of cream separator and, with this, and the development of appropriate techniques, the situation held great promise.

Another lesson learned from the experience in North Africa was the need to evaluate, in appropriate clinical settings, all products or procedures designed to treat sick persons. There was an established relation between the Navy and Cohn's group, and it was therefore logical that the two should cooperate in the continuing search for methods to make blood available to treat hemorrhage and shock. Accordingly, in 1956 the Navy established the Blood Research Laboratory (BRL) at the Chelsea Naval Hospital, Chelsea, Massachusetts, for collaboration with the Protein Foundation.

The Blood Research Laboratory

The BRL was established, under the direction of Captain Lewis L. Haynes, MC, USN, Chief of Surgery and Executive Officer of the Chelsea Naval Hospital, to study the clinical effectiveness of transfusions of previously frozen human red blood cells. The red blood cells were frozen with a high concentration of glycerol (approximately 45 percent) by the slow freeze-thaw technique; the Cohn Blood Fractionator was used to add and remove glycerol. The basic studies using this approach were carried out by the Protein Foundation, Jamaica Plain, Massachusetts, and were sponsored by a contract with the Office of Naval Research (ONR).

The laboratory space at Chelsea was in a stable that had been remodeled to serve as the tool shop for the Public Works Department. The space was renovated and the Cohn Blood Fractionator equipment and -80°C refrigeration units and some that maintained temperatures of -30°C were installed. A three-car garage was remodeled to serve as the storage area for the mechanical refrigeration units. The military personnel assigned to this laboratory were: a medical officer hematologist; a laboratory technician, and a biochemist from the Medical Service Corps; another laboratory technician; and a non-graded civil service laboratory helper. The Protein Foundation, through an ONR contract, provided a secretary, a nurse, and three laboratory technicians full time, in addition to consultative services of Dr. James Tullis and other members of the Protein Foundation.

The Surgical Research Laboratory at Chelsea Naval Hospital worked in collaboration with the Blood Research Laboratory. Dr. E. Watkins of the Lahey Clinic in Boston, and Dr. W. O'Brien, a Navy surgeon at the Surgical Research Laboratory, made measurements of the oxygen delivery characteristics of the cells after thawing. Changes in potassium transport during storage were also studied. The effects of transfusions of previously-frozen red blood cells in vascular surgery and in extracorporeal circulation were evaluated. The clinical experience gained between 1956 and 1962 with over three thousand units of previously-frozen red blood cells seemed to be favorable. In 1960 the first frozen blood bank for rare types of red cells was established at the Blood Research Laboratory in collaboration with the American Association of Blood Banks and the Massachusetts General Hospital of Boston. Under this program, the Laboratory receives rare bloods for freezing and storage, and prepares them for clinical transfusion when required.

The technique using the Cohn Blood Fractionator was found to the cumbersome. An attempt was made to simplify the system by using a plastic liner to wash the glycerolized red cells. However, the Blood Research Laboratory in collaboration with the Protein Foundation evaluated the prototype plastic liners and found them unsatisfactory.

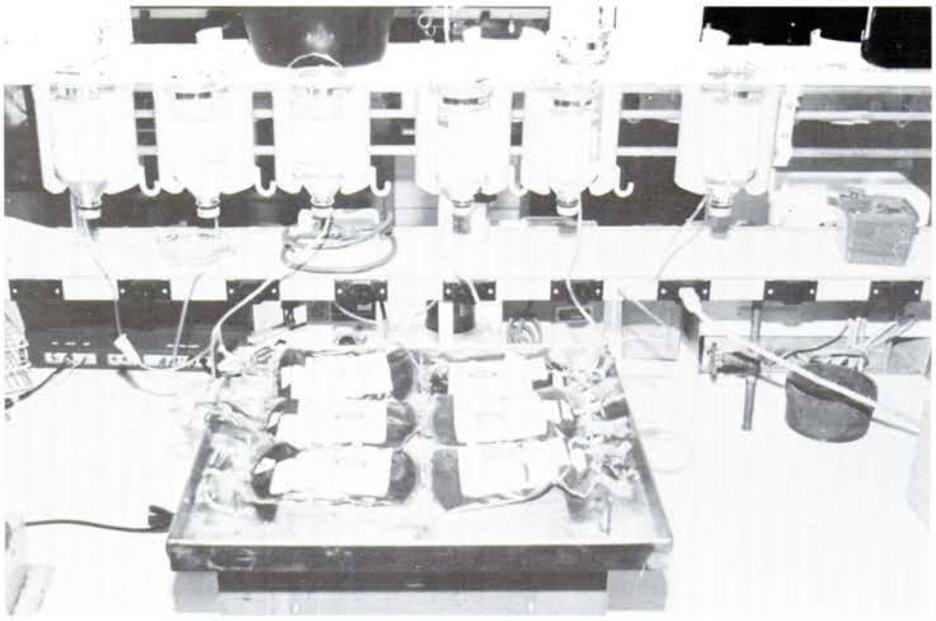
In 1962, Captain Haynes was transferred, and Lieutenant Commander M. E. Henderson, MC, USN, became director of the BRL. In July and August of that year serious reactions were unexpectedly observed in four patients who had received previously-frozen red cells. These patients had hemoglobin in the urine and developed renal failure. The hematologist assigned to the Laboratory, Lieutenant C. Robert Valeri, MC, USNR, studied these clinical problems. His investigations clearly revealed an immediate need to re-evaluate methods being used to clinically test previously-frozen red cells.

In October 1963, LCDR Henderson left the service and LT Valeri became the Laboratory director. The clinical problems created by transfusions of frozen red cells were studied extensively, and the results indicated that the most likely cause was outdated albumin solution that was being used as the resuspension medium for the thawed red cells.

By May 1964, bulk-volume freezing of red blood cells with high concentrations of glycerol, using the slow freeze-thaw technique and the Cohn Blood Fractionator, was feasible but still cumbersome. At that time, Dr. C. E. Huggins introduced the principle of a dilutional wash of glycerolized red cells using a low ionic solution. This procedure was attractive because it permitted freezing, thawing, and washing the cells in the same

plastic container. BRL began evaluation of this new method of removing glycerol from red blood cells.

In July 1965, the Blood Research Laboratory was officially severed from the Protein Foundation. With this separation the Laboratory received Civil Service billets for a secretary and two laboratory technicians and, on September 23, 1965, became the Naval Blood Research Laboratory (NBRL). The mission of this new Laboratory was to serve as the official test and evaluation center for blood and blood products for the Navy's Bureau of Medicine and Surgery (BUMED). The military complement was an officer-in-charge, assistant medical officer, two Medical Service Corps officers, and three laboratory technicians.



Clycerolizing red blood cells.

Freezing Red Cells

In 1966 the NBRL developed a systematic approach to the clinical evaluation of the preserved red cells as follows:

1. *In vitro* testing to establish optimum conditions for recovery of thawed previously-frozen red cells with removal of the additive (glycerol) and of the products of hemolysis.

2. *In vivo* observations of the survival of 10-ml aliquot transfusions of the subject's own preserved red cells to healthy volunteers. In this procedure full units of blood are collected, preserved, and prepared for transfusion. A 10-ml radio-active chromium-labeled sample is then reinfused as the test transfusion.

3. Clinical observations of full-unit homologous transfusions to stable, anemic medical patients who needed blood.

4. Clinical observations of multiple homologous transfusions to surgical recipients after operations of various types.

The studies made in the NBRL showed that freezing red cells by the Huggins technique was good enough to justify a feasibility study in combat zones in Vietnam to evaluate the practicality of a frozen-blood bank system as a supplement to the ordinary liquid-preservation program. The frozen red blood cells were collected principally in the Boston area in collaboration with Dr. C. E. Huggins at the Massachusetts General Hospital and Dr. A. Kliman at the Massachusetts Red Cross. Selected red cells were frozen in Boston and shipped in dry ice (at -80°C) first to Oakland, California, and then to Danang, South Vietnam, at the Naval Support Activity Hospital, or to the hospital ship *USS Repose*. The military personnel assigned to those special units in the combat zone had been trained or had worked at the NBRL. Funding for the units was provided by the BUMED. The evaluation of frozen blood at Danang was performed by Captain C. E. Brodine, MC, USN, the coordinator of the U.S. Navy's Blood Program, and by Lieutenant Commander C. S. Moss, MC, USNR. Frozen blood that had been stored at -80°C for less than one year was given in multiple-

unit transfusion (10 or more) to seriously wounded servicemen. The effects were carefully studied to evaluate the safety and efficacy of these transfusions, and the results conclusively demonstrated the feasibility of a frozen-blood bank in a combat zone. The blood so processed was shown to be safe and efficacious.

Because of the success with this initial experience between January and July 1966, frozen-blood banks were subsequently established aboard the newly commissioned *USS Sanctuary* in February 1967 and at Clark Air Force Base in the Philippines. The U.S. Air Force collaborated with the Navy's effort to establish frozen-blood banks by providing the support to transport necessary materials from Clark to Danang. A frozen-blood bank was established at Clark primarily to evaluate a frozen-blood product in a hemodialysis program which was being carried out at that hospital for the treatment of kidney failure that sometimes followed trauma.

With the increased number and activity of frozen-blood banks in South Vietnam, procurement of adequate amounts of selected red cells became more difficult. Facilities to collect and freeze red cells were established at Oakland Naval Hospital, Oakland, California, under the direction of Captain David Rulon, MC, USN, and then at the Naval Medical School, Bethesda, Maryland. With the growth of the frozen-blood bank program, the storage capabilities at Danang and Oakland were increased.

The feasibility study demonstrated that the Huggins technique for freezing red cells, while acceptable, had several disadvantages: namely, the large volume of wash solution (6.7 liters) required to prepare one unit of blood; the *in vitro* loss of red cells during processing (approximately 23-25 percent); and the excessive time required (approximately 50 minutes).

However, it was concluded that the clinical results of the transfusions to seriously wounded servicemen were highly satisfactory and that the Huggins freeze-preservation system was a useful supplement to the liquid blood program. It should be noted that at the beginning of the feasibility study (January 1966) the quantity of liquid blood in Vietnam was relatively small compared to the quantity available in June of 1967. Because of the deterioration of Huggins-preserved red cells stored at −80°C for longer than one and one-half years, the frozen-blood banks were removed from the *Santuary* and *Repose* and from Danang.

Equipment to measure recovery and function of red blood cells

Red Cell Research Continues

During the mid- to-late sixties the Naval Blood Research Laboratory contributed significantly to the establishment of methods of measuring the survival of red cells and of determining the usefulness of *in vitro* testing to help predict the post-transfusion survival of preserved red cells. Various *in vitro* biochemical measurements made on the stored blood cells (ATP, ADP, AMP, total nucleotide pool, glutathione level, glutathione stability, hexokinase level, glucose-6-phosphate dehydrogenase level, and glutathione reductase level) and various physical and structural measurements (red cell indices, density distribution of the red cells, osmotic fragility and lipid content) have been shown to be related to post-transfusion survival of

preserved red cells. Irreversibly damaged red cells are removed by the patient's body mechanisms following transfusion and this immediate loss can be detected only if independent measurements of the red cells of both recipient and donor are made at the time of the transfusion. This was possible through an ONR contract with Boston University. Dr. Charles P. Emerson performed the manual differential agglutination studies, while Dr. Irma O. Szymanski, a research associate at the University, measured the survivals in a device called an Autoanalyzer. The automated differential agglutination technique permits the simultaneous measurement of two red cell populations in the same person and permits the comparison of different methods of blood cell preservation in the same recipient. The different methods of preserving liquid-collected and-stored red cells and of freezing red cells (i.e., Cohn method, Huggins method, Pert-Krijnen-Rowe method, or other) have been evaluated by this approach.

An evaluation of previously-frozen red cells in extracorporeal circulation during cardiac surgery has been undertaken in collaboration with Boston University through the same ONR contract.

To physicians at the Chelsea Naval Hospital, where 306 severely wounded Marines were sent for treatment, the Vietnam conflict meant accelerated investigations into new treatments of battle-related injuries. This led to developments that also threw light on some old medical problems, with ultimate benefits not only to military personnel but to thousands of civilians. The Marines, who had serious and poorly-healed wounds in one or more extremities had been quickly taken to an aid station where bleeding was stopped and their blood loss corrected by transfusion. A puzzling finding came to light. Many of these young men belonged to the "Over Eighty Club;" that is, each had received over 80 units of blood to restore circulation to what appeared to be a normal state. This was puzzling because the normal blood volume is nine pints, and a significant number of the more than 80 pints transfused to these patients actually had been given after the bleeding had stopped. What had happened to this blood? It seemed to have vanished. What was the clinical significance of the "Missing Blood Symdrome?"

These questions, as well as the logical third one, "What to do about it?" were answered by the Naval Blood Research Laboratory. Dr. P. Biron of the Orthopedic Service at Chelsea observed that the usual treatment of wounds of the type discussed here was not producing the expected results. The process, debridement, is designed to remove the dead tissue and stimulate the growth of new tissue. The patient was given an anesthetic, and the minor procedure should not have created any difficulty. However, many of the Marines so treated had a life-threatening reaction, cardiovascular collapse. The initial impression was that the patients must have a reduced blood volume. But how could that be possible after so many transfusions? Moreover, the usual tests for anemia, the blood hemoglobin and hematocrit levels, were normal. LCDR Valeri was consulted, since the NBRL was equipped to make the appropriate tests. Blood volumes were studied and found to be low, sometimes by as much as 40 percent. The NBRL had the task of discovering why recipients with chronic wounds of the extremities destroyed transfused blood and why this phenomenon had not been recognized earlier. Valeri's extensive studies of the survival of transfused blood in wounded men made it possible for him to devise a cure for the syndrome–frequent transfusions to maintain normal red cell volume. This treatment greatly improved the health of the patients–wounds healed, appetite increased, moods became cheerful. Although the problem of the "Missing-Blood Syndrome" is still not completely solved, this contribution to the general medicine of trauma will soon be published in monograph form. It should be noted that, whereas the studies made at Chelsea defined the mechanisms responsible for the disorder and indicated its treatment, they did not elucidate the cause. Etiologic studies are pursued at research institutes such as the National Institutes of Health, where research is theory-oriented. At Chelsea, and facilities like it, the studies have consistently been patient-oriented.

Among practical problems studied at the NBRL was the separation and preservation in liquid or frozen state of the blood platelets, the blood elements essential for clotting. This can now be done, despite the many difficulties encountered in handling these fragile elements. This is an important contribution, for many patients in civilian and military practice need to be given blood platelets to overcome a deficiency of their blood-clotting mechanisms.

Salvaging Outdated Blood

Another main effort of the Naval Blood Research Laboratory during the past decade has been to develop and evaluate procedures for salvaging outdated blood stored in blood banks. It will be recalled that liquid-stored blood must be discarded three weeks after collection in the most commonly used preservative solution (CPD mixture). However, these red blood cells, although able to stay alive for up to three weeks depending on the preservative solution used, do not transport oxygen normally after about the first week. The problem became multifaceted, viz., to salvage outdated blood;

to provide red blood cells with normal oxygen-delivery capacity after a week or so of liquid storage; and finally, to develop ways of producing red blood cells with different oxygen-delivery capacities to be used as required under different clinical circumstances. Red blood cells contain a substance called 2,3-diphosphoglycerate, a glucose derivative generated under the influence of phosphorus compounds inside of and outside the red blood cells. This compound, generally referred to as 2,3-DPG, regulates the ability of the hemoglobin in the red blood cells to take up oxygen in the lungs and to give it up in the tissues. The Laboratory, by ingeniously blending its competence in freezing, rejuvenating, and measuring the function of the red blood cells, has devised simple, easily standardized methods of generating and storing red blood cells with a range of desired oxygen-delivery functions. This important accomplishment was reported at an international conference on oxygen transport held in Newton, Massachusetts, in April, 1979. Captain Valeri was chief organizer of the Conference, and a number of other Laboratory personnel participated.

The physiological and chemical applications of the modified blood are currently under intensive study, both in man and in baboons, at Boston University School of Medicine, at the Peter Bent Brigham Hospital and Harvard Medical School, and at other nearby teaching and research centers. The location of the NBRL in the midst of these institutions has aided the rapid prosecution of these studies.

Cell washing system

ONR Funded Laboratory

All of these activities have been carried on despite interruptions and dislocations due to administrative changes. In 1974, there was a change that enhanced the efficiency of the NBRL. In that year, the Laboratory was transferred from the control of the BUMED to the newly established Naval Medical Research and Development Command. However, in 1976, the First Naval District was disestablished and, with the earlier closing of the Chelsea Naval Hospital in 1974, the NBRL sought other quarters that would keep it within the Boston medical academic community. In 1976, the Laboratory was moved to temporary quarters in the Talbot Building, a decrepit structure, albeit of great historical importance, on the campus of the Boston University School of Medicine. The New England Nuclear Corporation donated a building to the Navy and in 1977, after extensive alterations had been made, it became the home of the Laboratory and, hopefully, will remain so indefinitely. These two moves of facilities, including equipment both heavy and delicate, were made without noticeable diminution of the activities of the NBRL.

When the First Naval District was disestablished, the Laboratory came under the area coordination of the Commandant, Fourth Naval District, Philadelphia, Pennsylvania. In 1978, the NBRL was disestablished as an in-house research facility and has been maintained since then by an ONR contract with the Boston University School of Medicine. This has increased the NBRL's ties to the medical academic community and will thereby enhance its function. NBRL's leadership continues in studies on:

- frozen blood preservation;
- the rejuvenation of over-age stored liquid blood;
- the preparation of red blood cells with the specific oxygen-delivery qualities needed in different clinical conditions;
- the preparation of separated blood components and cells with optimal functions for clinical use, among other things.

Above all it is devoted to the development of scientifically-sound, clinically-determined efficient and effective technological solutions to all problems related to field use or hospital use of blood and any of its components as needed in the treatment of sick or injured persons. In these areas the NBRL has been accorded worldwide recognition as a leader, and also as a training ground for researchers. ■

APPENDIX

Chronology of Accomplishments

1956	Establishment of the Blood Research Laboratory at Chelsea Naval Hospital, Chelsea, Massachusetts.
1957	Successful freeze-preservation of red blood cells using the Cohn Blood Fractionator.
1960	Establishment of the first frozen blood bank for rare blood types.
1962	Studies initiated to evaluate the quality of preserved red blood cells.
1964	Evaluation of the Huggins dilutional wash procedure.
1966	Successful freeze-preservation of red blood cells using the Huggins technique.
	Establishment of frozen blood banks at Danang, South Vietnam; Clark Air Force Base in the Philippine Islands; and aboard the hospital ship *USS Repose.*
	Clinical evaluation of frozen red blood cells at the Chelsea Naval Hospital and in combat areas.
1967	Establishment of a frozen blood bank aboard the hospital ship *USS Sanctuary.*
	Establishment of red blood cell collection and freezing centers at Oakland Naval Hospital, Oakland, California, and at the Naval Medical School, Bethesda, Maryland.
	Evaluation of the Arthur D. Little reusable stainless steel bowl to wash frozen red blood cells.
1965-1967	Development of an automated differential agglutination (ADA) technique to measure red blood cell survival.
	Freezing and evaluation of low concentration (20% W/V) glycerolized red blood cells.
1968-1973	Evaluation and treatment of the "Missing Blood Syndrome." Extensive clinical evaluation of the hypovolemic anemia of trauma.
1969-1971	Liquid preservation of human platelets.
1969-1971	Establishment of procedures to salvage outdated human red cells by biochemical modification prior to freeze-preservation with 40% W/V glycerol at −80°C or with 20% W/V glycerol at −150°C.
1971	Salvaging of outdated red blood cells.
1971-1973	Measurement of oxygen content of blood using the fuel cell.
1971-1975	Establishment of a model study in man to determine the hemostatic effectiveness of autologous platelets preserved by liquid and freeze-preservation methods. Treating normal volunteers with aspirin produces a thrombocytopathy which can be corrected by reinfusion of autologous preserved platelets.
	Establishment of methods to biochemically modify baboon red blood cells with normal 2,3 DPG, 1-1/2 to 2 times normal 2,3 DPG, and 3 times normal 2,3 DPG prior to freeze-preservation with 40% W/V glycerol at −80°C or with 20% W/V glycerol at −150°C.
	Establishment of procedures to improve the oxygen transport function of human red cells by biochemical modification of indated red blood cells prior to freezing with the high or low glycerol freeze method.

1971-1978	Studies of baboon red cells, platelets, and granulocytes to demonstrate the feasibility of using the baboon to study methods of isolating and preserving these cells. Baboon red cells, platelets, and granulocytes can be isolated and preserved in much the same manner as human cells have been successfully handled in the past.
1972-1973	Successful isolation of platelets from a single unit of blood by serial differential centrifugation and freeze-preservation with 6% DMSO at 2-3 C per minute at -80°C for at least 8 months.
1973	Freeze-preservation of red cells with improved capacity to deliver oxygen.
1973-1975	Physiologic studies in baboons to demonstrate an increase in cardiac output during the immediate 2-6 hours after transfusion of red cells with a respiratory defect (increased affinity for oxygen) after red cell storage in the liquid state at 4°C.
1973-1978	Liquid and freeze-preservation of platelets.
1974	Studies on removal of the hepatitis B antigen from blood—effects of washing, glycerolization and washing, and glycerolization freezing and washing, and studies to evaluate the reduction in clinical hepatitis.
	Study of the plasticizer, di-2-ethylhexylphthalate (DEHP) in whole blood, platelet concentrate, and platelet-poor plasma.
	Study of platelet circulation and function during hyperbaric exposure. Collaborative study with Naval Submarine Medical Research Laboratory, Groton, Connecticut.
1974-1978	Study of formation and removal of microaggregates in previously-frozen washed red cells.
1975-1977	Establishment of methods to salvage outdated red cells by biochemical treatment prior to freeze-preservation with 40% W/V glycerol can be at -80°C for at least 3-1/2 to 4 years. Excellent recovery of red cells, acceptable 24-hour post-transfusion survival, and normal oxygen transport function have been maintained.
1975-1978	^{51}Cr labeling of human lymphocytes, granulocytes, monocytes, and platelets using velocity sedimentation through a phosphate-buffered saline-bovine serum albumin gradient.
	Establishment of a method to evaluate the circulation and function of red cells perfused through a blood oxygenator.
1976	Studies to evaluate granulocytes isolated from blood by elutriation.
1976-1978	Studies to demonstrate that red blood cells with increased 2,3 DPG levels (1-1/2 to 2 times normal) improve myocardial function immediately following extracorporeal bypass.
	Attenuation of the increased affinity of red cells during hypothermia by biochemical modification of red cells to increase the 2,3 DPG level to 1-1/2 to 3 times normal prior to freeze-preservation.
	Freeze-preservation of human red cells in the primary collection bag.
1977	*In vitro* assay of platelet function by measuring thrombin-induced release of 5-hydroxytryptamine.
1978	A new system for freeze-preservation of human red cells — higher quality at lower cost.
	Successful freeze-preservation of platelets isolated in large numbers from a single donor.

Phenomena of Instability: Fracture Mechanics and Flow Separation

by

G. C. Sih

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On a calm evening in January of 1943, the *Schenectady* T2 tanker suddenly broke in two at dockside in Portland, Oregon. The ship jackknifed with the bow and stern settled into the river bottom. Incidents of this type were not uncommon during World War II when ships were produced in large quantities with insufficient experience in and knowledge of the design of welded structures. The monolithic nature of nonredundant welded structures can be highly constrained and provide continuity such that catastrophic fracture can arise from minute defects such as weld cracks or arc strikes. As a result, the Navy intensified fracture mechanics research[1, 2, 3] during the post-war period. The Office of Naval Research has continuously supported work in this area so that the new developments in fracture mechanics can lead to better designs and materials for ship structural components. Today, engineers and scientists from many disciplines all over the world are contributing to fracture mechanics with great intensity. This can be clearly evidenced by the increasing number of open literature publications, international conferences, and engineering society activities.

Besides ships, catastrophic fractures have also occurred in steel structures such as tanks, pressure vessels, bridges, gas transmission lines and others. Needless to say, there is an urgent need to understand the mechanisms and conditions controlling fracture. The philosophy adopted in material testing is that laboratory data collected on the smaller test specimens could be translated for use in the design of large size structures. Such an approach, however, can be deficient. A small metal specimen may exhibit fictitiously high ductility while the same material in a larger size can behave in a brittle fashion. Clear evidence of this has been observed in the failures of large storage tanks and ships under service conditions. Post-mortem examination of the broken pieces of the tanks and the fractured

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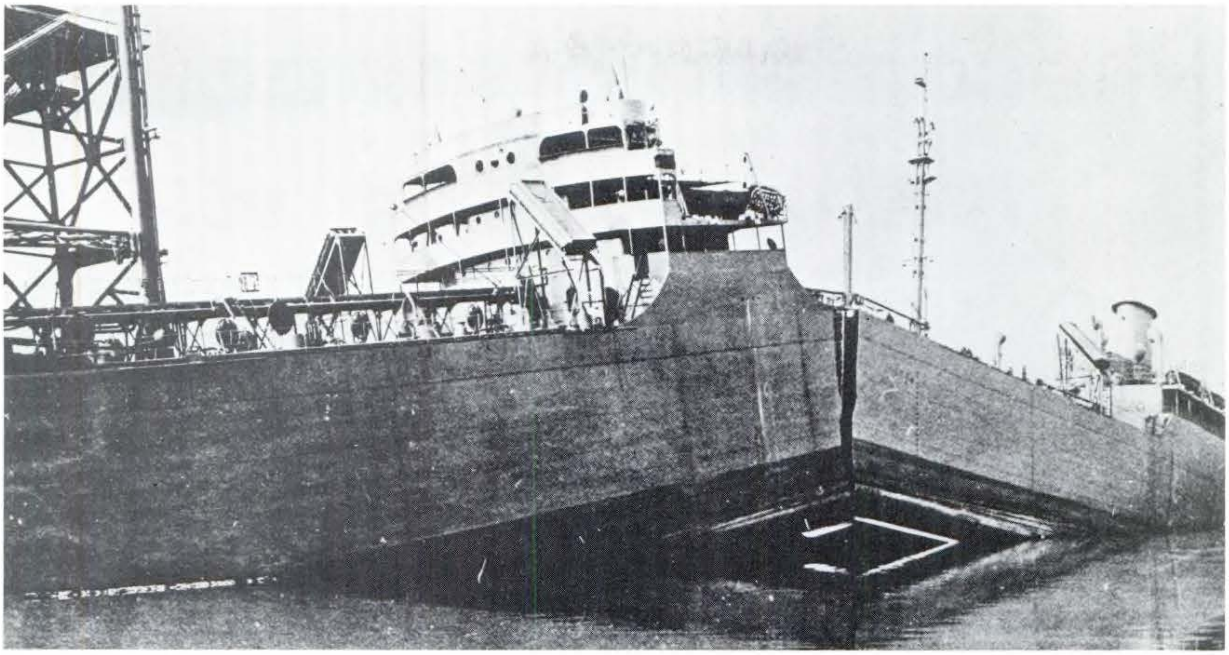


Courtesy of Naval Research Laboratory

surfaces of ship plates did not disclose any ductile fracture surface appearance or zones of permanent deformation such as one actually sees on the much smaller laboratory specimens of low carbon steels tested at the same service temperature. (Failures in ships cannot be explained simply as metals operating at low temperatures alone but involves the insufficient knowledge on the part of the structural engineer regarding the combined influence of temperature, rate of loading, geometry and size.)

This is attributed to the so-called "size effect" phenomenon that is still not completely understood. Full-scale and/or model testing remain as necessary steps in the design of engineering structures.

Questions such as these have been pondered for many years with a bewildering array of theories and experiments proposed by the solid state physicists, dislocation theorists, continuum mechanists, materials testers and structural engineers. Admittedly, the failure of a solid can be traced to its microstructure and arrangement of its constituent atoms. However, our inability to analyze the problem in one step covering more than ten orders of magnitude on the length scale made it necessary to divide the investigation into three loosely defined divisions: atomic, microscopic and macroscopic, leaving out the structural division which extends the length scale by another three or more orders of magnitude.

Although continuum modelling of the material structure can be done at the different scale levels, it is not clear at present how the results are related. In addition, the basic question of how the individual material constituents affect the response of the constituent-aggregate as a whole is still far from being answered. Ideally speaking, matter can be represented by a regular three-dimensional array of atoms and from a knowledge of this arrangement it should be possible to deduce the mechanical properties of the solid and to analyze its failure behavior. Attempts in this direction have been frustrating and have not brought us any closer to the solution of the basic problem of material failure. Because of space limitation, this article will not delve into the details of atomic or microscopic models of solids.

Fracture mechanics basically owes its development to the theory of continuum mechanics. It focuses attention on the onset of instability of a solid containing imperfections in the form of cracks rather than concentrating entirely on the deformation history of the solid. One of the unique features of fracture mechanics is the parameter associated with crack instability, that serves as a material constant and can be used to rank the resistance of materials to fracture. Such a constant has been generally referred to as *fracture toughness*, designated by G_{1c} (or K_{1c}, which differs from G_{1c} by a constant).

It may appear strange that flow separation should enter into the title of this article which is predominantly devoted to the fracture mechanics of solids. Insofar as the phenomenon of instability is concerned, however, it is conceivable that the separation of solid and fluid

may share the same criterion of instability. This possibility was first realized in 1972 during an investigation of the maximum potential energy density criterion[4] or the minimum strain energy density criterion as applied to the fracture of solids. It was then discovered that the same criterion could be used to predict flow separation. A technique for computing (either numerically or analytically) points of separation of turbulent flow past solid bodies was developed and a number of example problems were solved. The results agreed surprisingly well with the available experimental data. This quick and accurate way of determining flow separation is considered to be a major improvement over the present methods of locating turbulent separation points. Such a capability can be programmed into the computer and cast a new outlook on the design of Navy vehicles of varying shapes that run in water, air, and at the air-sea surface. For the first time, it may be possible to optimize the complicated profiles of various vehicles in terms of reducing the wake size by delaying separation.

Fracture Mechanics

Fracture Toughness

Fracture mechanics in its simplest form relies on the concept that the "worst flaw or defect" in the structure does the damage. Mathematically, this defect is idealized in the form of a line crack with sharp tips in an elastic continuum. The crack extension process is assumed to involve the conversion of elastic energy to the creation of new free surface. The energy dissipated in this process is called the *energy release rate,*[5] G_1, whose critical value, G_{1c}, is identified with the onset of rapid crack extension. It is also a common practice to relate G_1 to the stress intensity factor parameter[2], K_1:

$$G_1 = \frac{1 - \nu^2}{E} K_1^2 \qquad (1)$$

in which ν is the Poisson's ratio and E the Young's modulus. The critical value, G_{1c} (or more often K_{1c}), is called the fracture toughness and has been measured for a host of engineering materials (see Table I). Test procedures for determining the toughness of metal alloys are available through ASTM[6].

The underlying assumption of the classical theory expressed by the equation in (1) is that the load must be applied to the crack and that the crack must always extend straight ahead. It follows that the mathematical crack has to be perfectly sharp giving rise to a $1/\sqrt{r}$ stress singularity such that the stress can increase without bound as the radial distance r measured from the crack tip diminishes. Disturbing as it may be on physical grounds, this mathematical feature is attractive and permits a direct analytical determination of the stress intensity parameter.

Table 1. Fracture toughness values[10] for some engineering materials

Material	Critical energy release rate G_{1c} (lb/in)
Key Steel	5.71×10^2
Brass	3.43×10^2
Teak Wood	6.85×10
Cast Iron	4.57×10
Polymethylmethacrylate	5.71
Epoxide Resin	3.77
Alumina	4.57×10^{-1}
Glass	4.57×10^{-2}

The early works on stress analysis[7, 8, 9] revealed that K_1 can be extracted simply from the crack-tip stress field rather than by laboring with the complex nature of the energetic treatment involving the direct calculation of G_1. This realization was no small achievement as it led to the evaluation of stress intensity factor solutions for a multitude of crack configurations and loading conditions. More importantly, it offered the possibility of extending fracture mechanics to structural applications. A variety of stress intensity factor solutions for cracks in three-dimensions, plates and shells, composite materials, etc., can be found in a Lehigh University publication: *Handbook of Stress Intensity Factors*[11].

It soon became apparent that a general description of the crack border stress state requires the knowledge of three stress intensity factors K_1, K_2 and K_3. The original fracture criterion based on K_1 reaching a critical value, K_{1c}, (or G_1 reaching G_{1c}) is no longer adequate. The involvement of all three stress intensity factors requires some combination of these factors reaching a critical value[9]:

$$f(K_1, K_2, K_3) = f_{cr} \qquad (2)$$

A mixed mode fracture criterion is thus needed for extending the concept of fracture mechanics to situations where the structure is subjected to combined loadings. Attempts have been made to extend the energy release rate concept to the mixed mode situation. The difficulties and uncertainties encountered in

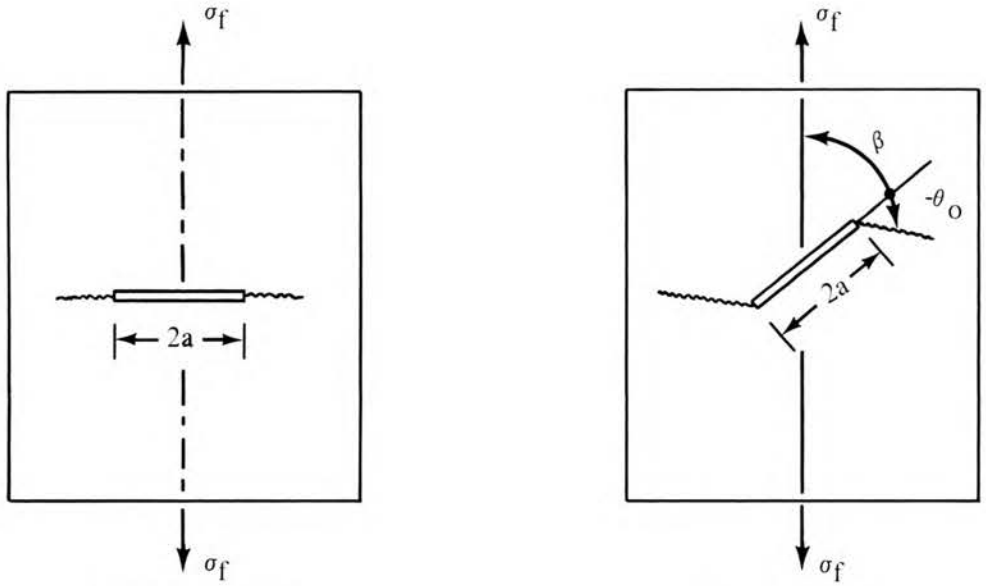


Figure 1. Line crack in tension.

the numerical calculations, however, make this approach infeasible.

Strength and Failure Stress

One of the objectives of fracture mechanics is to seek a better understanding of the relationship between the strength of a material and its basic properties. The difference between calculated and measured values of the strength of materials has been particularly disturbing. The terms "strength" and "failure stress" are often used but seldom defined in a precise manner. The term strength is conventionally associated with the stress level at which a failure of some kind has occurred in a standard test specimen. Clearly, the strength will depend upon the failure mode, which may involve the simple loss of structural stiffness due to inelastic or elastic deformation, or material separation of a catastrophic nature, or the combination of both.

The analysis procedure adopted in fracture mechanics for estimating the service failure stress assumes that the test specimen contains a crack-like defect. The failure criterion for crack extension is applied by equating a function of the applied stress σ_f and the geometry of a structural component to a material constant, the fracture toughness. For a large plate containing a line crack of length 2a (Figure 1a), the failure stress can be obtained by setting $K_1 = K_{1c}$:

$$\sigma_f = \frac{K_{1c}}{\sqrt{\pi a}} \tag{3}$$

In situations where the load and crack symmetry is not preserved as in the case of Figure 1B, an easily usable theory based on the strain energy density factor

$$S = A_{11}K_1^2 + 2A_{12}K_1K_2 + A_{22}K_2^2 \tag{4}$$

has been proposed[4]. In equation (4), the coefficients A_{ij} (i,j = 1,2) depend on the material properties and the fracture angle θ_o. The factor S represents the product of the radial distance, r, multiplied by the strain energy density function, dW/dV, commonly employed in elasticity. The function dW/dV decreases monotonically with the crack tip radial distance r as illustrated in Figure 2. The critical value of S, S_c, corresponds to incipient fracture and is equal to r_o (dW/dV) where r_o is the radius of the core region outside which the failure of an element is assumed to take place. The position of this element is found by minimizing S with respect to θ, i.e., $\partial S/\partial\theta = 0$. For the inclined crack problem in Figure 1b, the failure stress σ_f is found by setting $S_{min} = S_c$:

$$\sigma_f = \left[\frac{S_c}{aF(\beta,\theta_o)}\right]^{1/2} \tag{5}$$

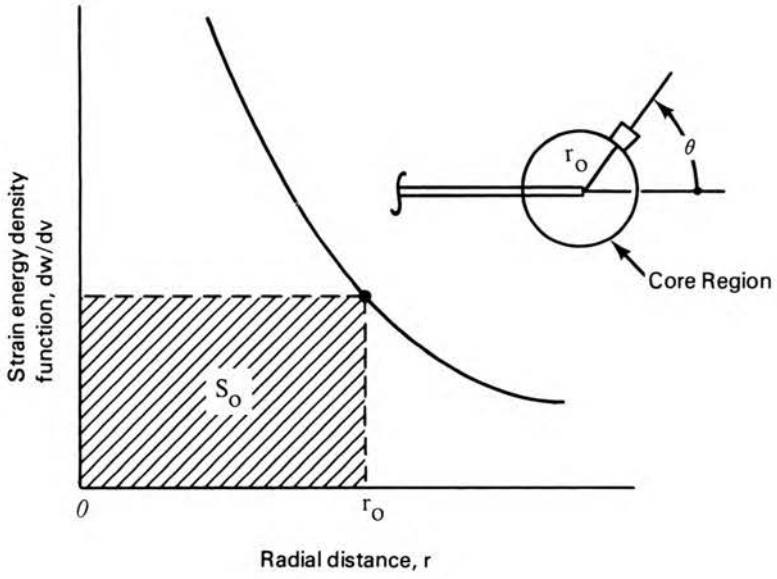


Figure 2. Variation of strain energy density function with radial distance.

in which $F(\beta,\theta_o)$ is an analytically determined function. The critical value S_c, being characteristic of the material, remains constant regardless of the crack orientation and can be determined in the same kind of tests used to obtain K_{1c}. In fact, the relation

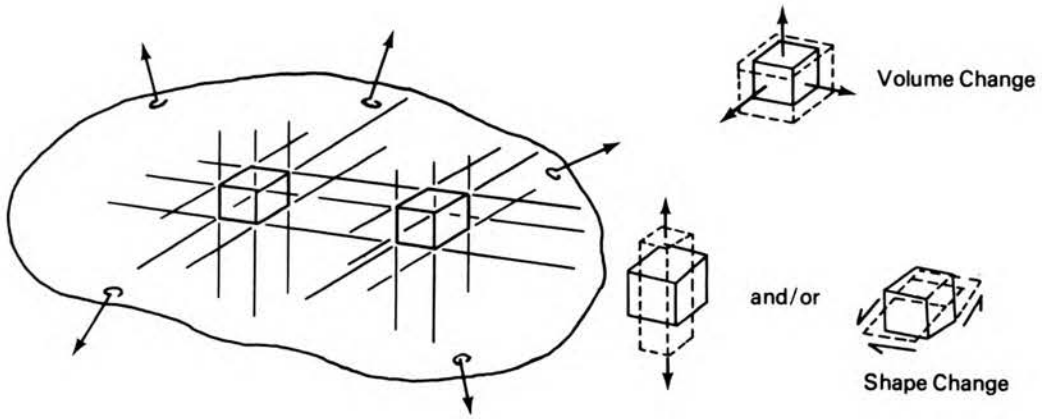
$$S_c = \frac{(1+\nu)(1-2\nu)K_{1c}^2}{2\pi E} \qquad (6)$$

can be used to convert the existing data on G_{1c} or K_{1c} to S_c[12]. Direct measurements of S_c or $(dW/dV)_c$ have also been reported[13].

Strain Energy Density Concept

The basic concept of the strain energy density theory[4] can be best conveyed by visualizing an idealized continuum to consist of a three-dimensional array of minute cubic blocks (Figure 3a). As the solid is stressed, each of the blocks will undergo volume change (dilatation) and shape change (distortion), Figure 3b. The corresponding stored energy per unit volume is $(dW/dV)_v$ for dilatation and $(dW/dV)_d$ for distortion. Failure by fracture or yielding will then depend on the proportion of $(dW/dV)_v$ and $(dW/dV)_d$ in a particular block. Excessive dilatation is associated with fracture while excessive distortion is associated with yielding. As a matter of fact, $(dW/dV)_d$ is precisely the quantity used in the Huber-von Mises-Hencky yield criterion. Ideally speaking, if the strain energy density is uniformly distributed throughout the solid, then each block will dissipate the same amount of energy and fail at the same time. Such a condition, of course, cannot be realized in practice where the strain energy density function will vary from point to point. It is at the valleys and peaks of dW/dV where failure will most likely occur. Their locations can be determined from the stationary values of the strain energy density function.

If the solid contains a crack (Figure 4a), then attention is focused on an element at a distance r from the crack tip and it suffices to consider the factor $S = r(dW/dV)$. Figure 4a shows that under symmetric loading, distortion or yielding is off to the sides of the crack and dilatation associated with fracture is directly ahead. The location $\pm\theta_p$ correspond to S_{max} and $\theta_o = 0$ to S_{min}. The ease with which S_{min} and S_{max} can be calculated will be shown to play a vital role in the prediction of crack trajectories.



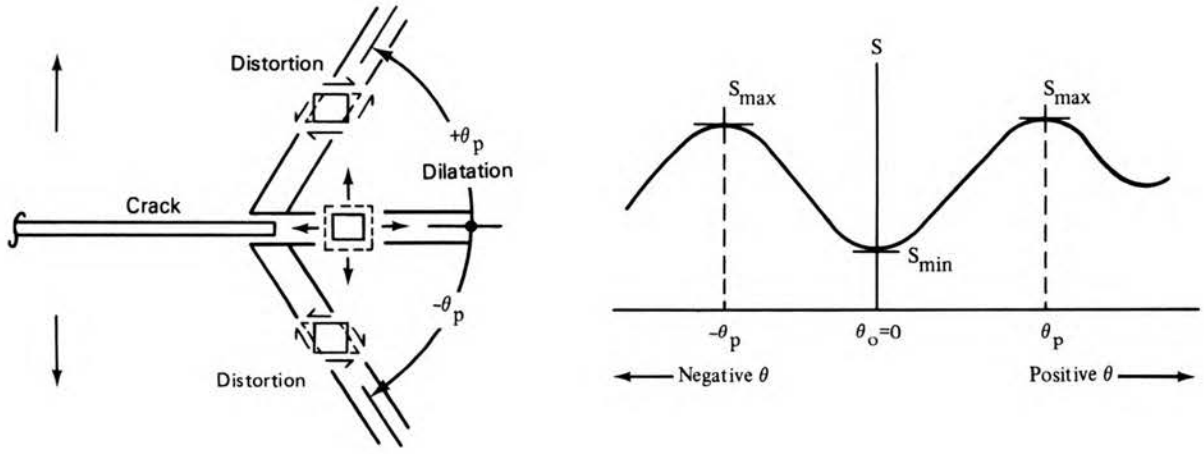
a. Solid composed of cubic blocks

b. Volume and shape change

Figure 3. Idealized continuum.

Prediction of Crack Trajectory

Until recently, no suitable failure criterion could be found to render a reliable prediction of the crack trajectory. This capability, if exercised in the initial design, can conceivably control crack propagation within a predetermined region such that the integrity and performance of the structure are always maintained. In other words, the loads can still be safely redistributed in the presence of cracks. This know-how depends directly on the ability to control the direction of crack propagation and will be illustrated through some examples on test specimens.



a. Distortion and Dilatation.

b. Stationary values of S

Figure 4. Interpretation of Smin and Smax.

Returning to the angle crack specimen in Figure 1b, elements ahead of the crack with minimum strain energy density[14] have been computed for different crack angles β. The locus of these elements forms a path of S_{min} (Figure 5), along which crack propagation is assumed to occur. Crack trajectories on plexiglass plates have been determined experimentally. Photographs of actual crack trajectories for $\beta = 30°$ and 45° are reproduced schematically in Figures 6a and 6b, respectively. Attached to each figure is a trace of the mathematically predicted path for a crack of the size shown in the original photograph. The agreement is observed to be very good for the cases illustrated.

Crack path prediction studies have also motivated experimentalists to determine the sensitivity of nonalignment of load and/or variations in specimen geometry. A good example is the commonly observed phenomenon of shear lips in metal fracture that results in an unsymmetric pattern of fracture along the line of seemingly symmetric loading before material separation. This can be explained and predicted as a consequence of nonalignment of load with the crack plane. Figure 7a shows that if the crack plane is deviated by a small amount δ from the plane of symmetry, then both shear lips will be retained on one of the broken pieces of metal (Figure 7b). On the other hand, a slight tilt of the crack plane about the center line (by an angle ω; see Figure 8a), produces a skewed pattern of shear lips (Figure 8b).

Cracks tending to turn rather than run straight also have been frequently encountered in the compact tension specimen. The common practice of machining side grooves on the specimen to guide the crack is often ineffective, particularly for the high strength material. This problem was not understood in the past and has driven many experimentalists into frustration. The use of standard formulas that fail to account for load and/or specimen nonalignment in material testing can lead to erroneous conclusions. It is good practice to precede experiments with a fracture analysis for determining the allowable tolerances on load alignment and specimen geometry. The compact tension specimen has been analyzed on the basis of the strain energy density theory and shown to be very sensitive to deviations from symmetry. It is worthwhile to know that the location of the crack tip tends to govern the direction of crack growth. As long as the crack tip lies in the line of load symmetry, the crack will run straight in a compact tension specimen.

The simplicity of the foregoing approach suggests the possibility of applying such concepts to forecast the path of failure in many complex situations. Indeed, crack growth in three dimensions can be analyzed in the same way[15]. The application to the design of a real structure may be involved but not difficult and should materialize in the foreseeable future.

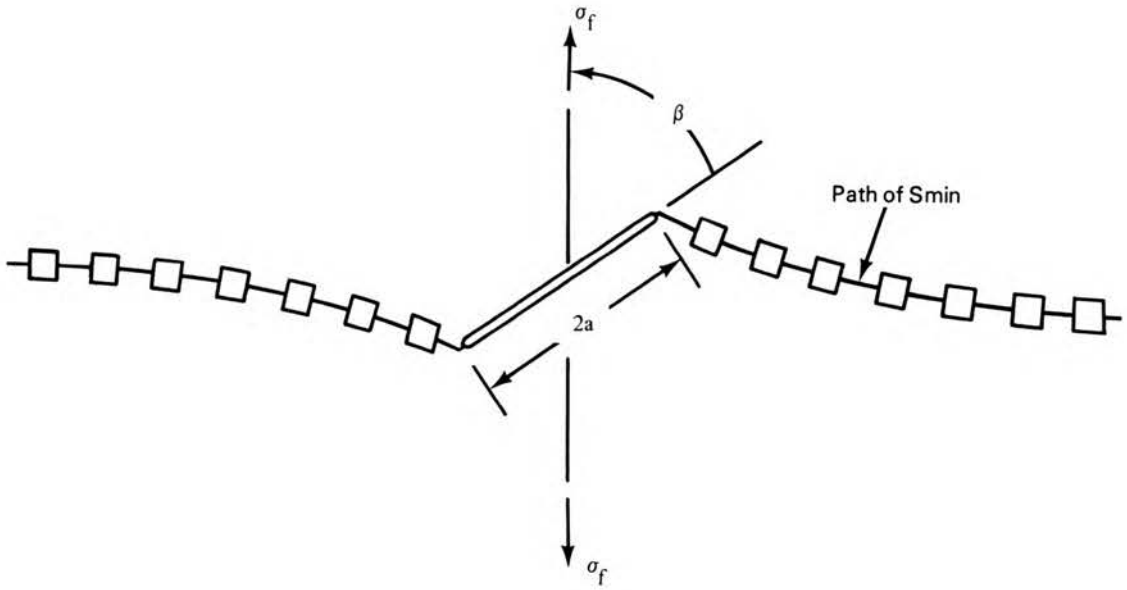
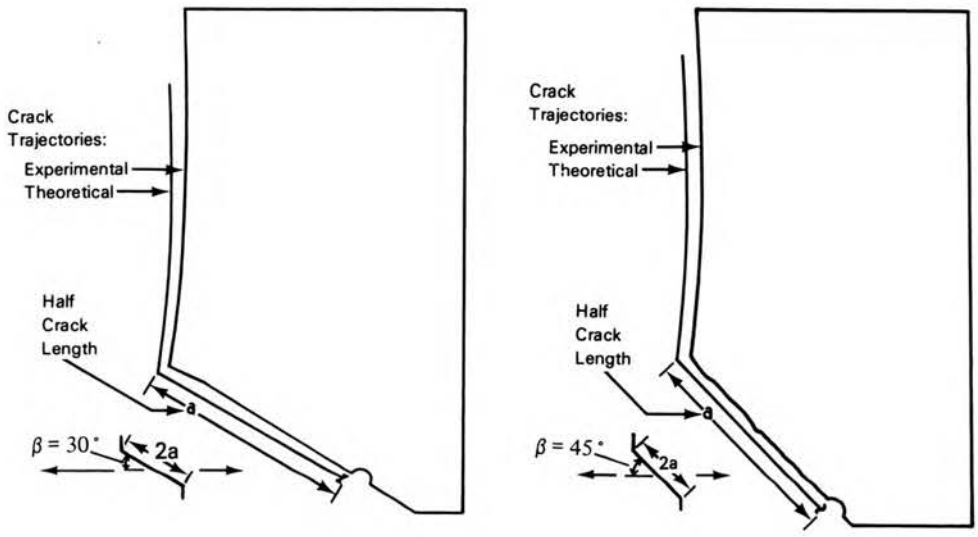


Figure 5. Crack trajectory following the bath of Smin

Ductile Fracture

One of the least understood problems in fracture mechanics is perhaps that of crack propagation preceded by irreversible distortion of the solid. In the presence of plastic deformation, it is no longer an easy task to sort out the portion of energy dissipated by crack propagation unless a detailed three-dimensional elastic-plastic fracture analysis is carried out. (Many of the two-dimensional elastic-plastic fracture analyses fail to account for necking of the specimen with finite dimensions and may not be realistic.) A descriptive account of the ductile behavior of a tensile bar is given in Figures 9a to 9d. Figure 9a gives the fracture path for a relatively brittle material that separates along a flat plane with little or no plastic deformation. The more ductile behavior is exhibited by necking and plastic deformation before failing in a cup-and-cone fashion (Figure 9b). An important point to be made here is that both Figures 9a and 9b imply the release of elastic energy since the crack propagates in the elastic region. Hence, the energy dissipated to extend a unit crack area at instability is the same. This means that the same fracture toughness value can be applied to both specimens (i.e., Figure 9a, brittle behavior and 9b, ductile behavior). The very ductile behavior is achieved by yielding across the specimen section as illustrated in Figure 9c and the intensities of yielding will again be nonuniform and distributed in accordance with the amount of distortion and dilatation experienced by the material elements. The pattern is shown in Figure 9d and is referred to as second degree of yielding. Fracture will again be of the cup-and-cone type but its size will be comparatively smaller than that developed in Figure 9b. In a relative sense, the material in Figure 9d is said to be more ductile than that of Figure 9b. Continuum mechanics analyses have been performed to account for the different degrees of material ductility and the cup-and-cone feature of fracture[15]. This work is not complete and is still in the stage of research.

The major conclusion from the preliminary research findings is that the fracture toughness, being a measure of the energy dissipated at the instant of incipient fracture, is the same for both the brittle and ductile material if the creation of macroscopic crack surface takes place in the elastic portion of the elastic-plastic material (Figure 9b). This interpretation at least explains why a crack may start in a ductile fashion and then complete its propagation as a brittle fracture. It is the failure stress that will vary as a function of material ductility and not the fracture toughness. Hence, according to the strict definition of fracture toughness[16], it



a. $\beta = 30°$ b. $\beta = 45°$

Figure 6. Predicted abd actual crack trajectories.

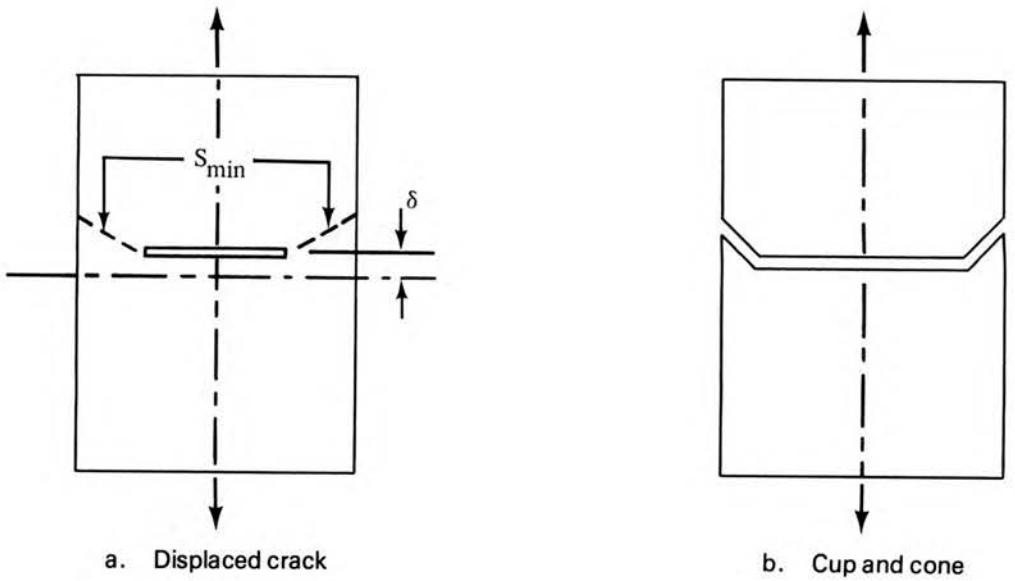


Figure 7. Symmetrical shear lips

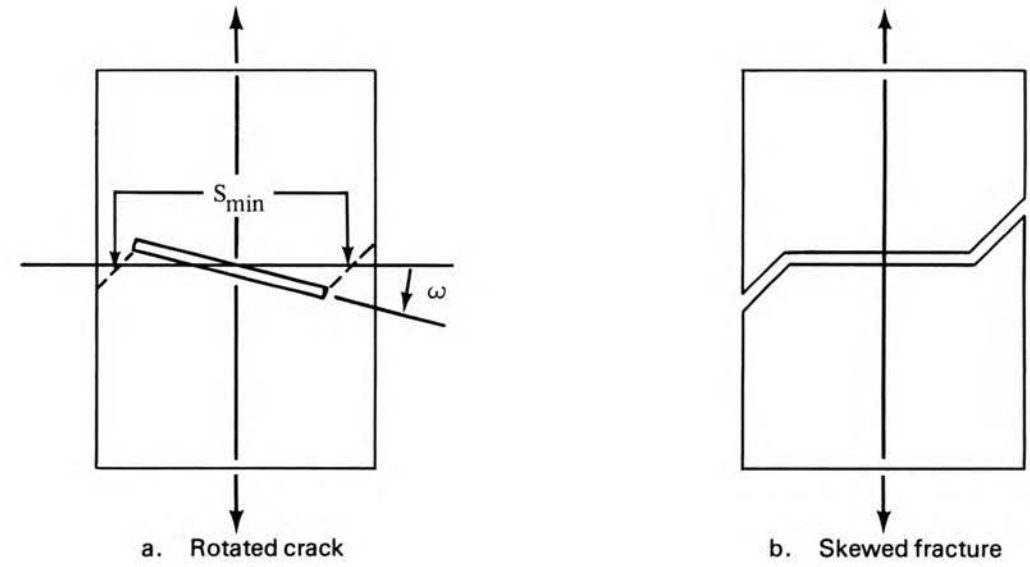


Figure 8. Skew-symmetrical shear lips.

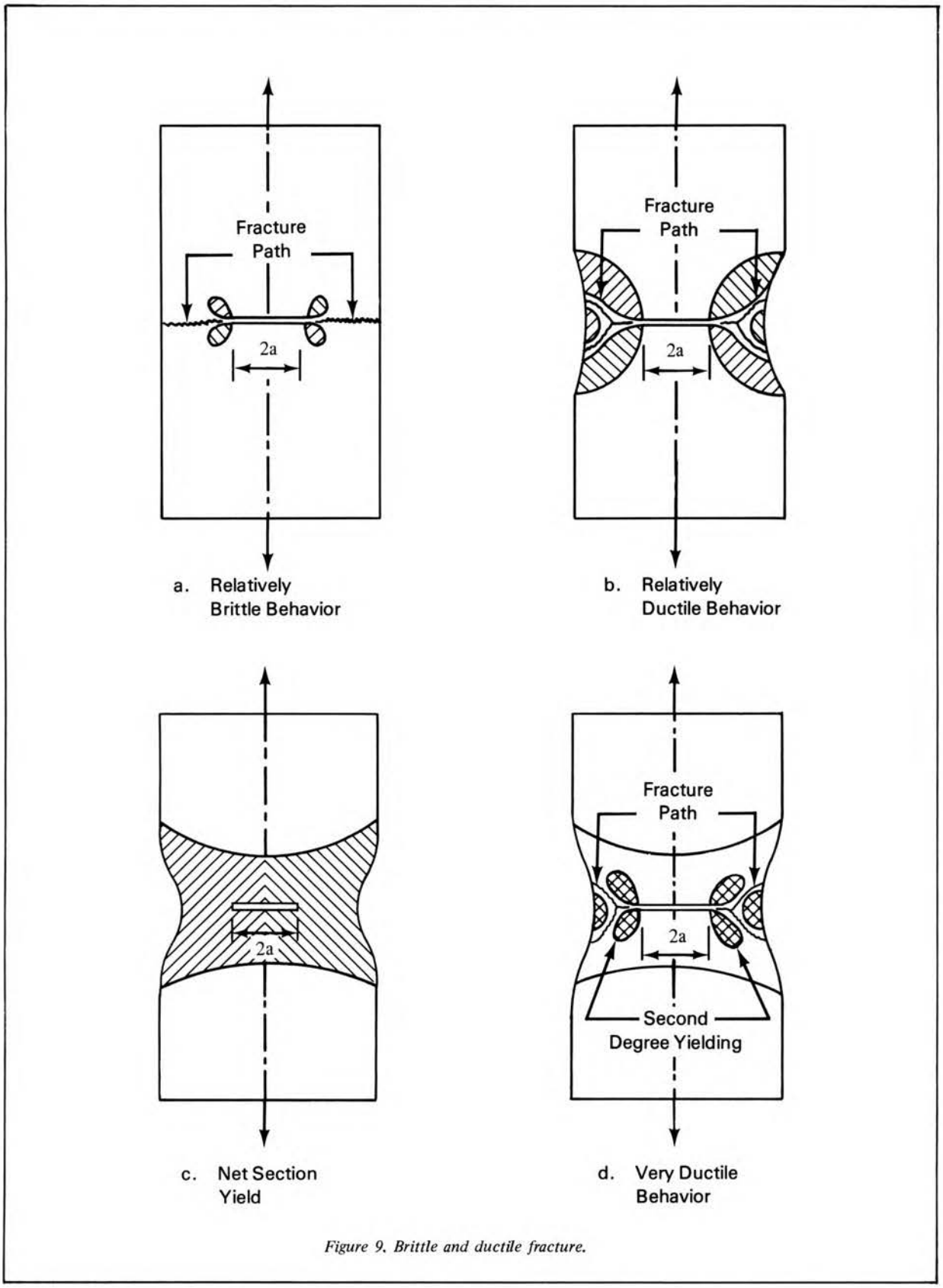


Figure 9. Brittle and ductile fracture.

would be inaccurate to say that the ductile material has a higher fracture toughness than the brittle material.

Flow Separation

One of the valuable developments of research is the unexpected spin-off of ideas to another discipline. In 1972, when the strain energy density criterion was first advanced[12] for analyzing the instability of solids with cracks, it appeared that the same concept could be applied to predict the separation of flow past solid bodies. After all, the criterion of instability is in no way restricted by the constitutive law of the continuum as long as the phenomenon of instability prevails, whether it be the sudden separation of a solid or a fluid. Since prediction of surface separation in solids uses the stress or energy state of the solid prior to separation, the natural question is whether this approach can be applied to predict fluid separation. Perhaps the idea was prematurely disregarded on account of the classical notion that fluid separation must necessarily be associated with the presence of a viscous boundary layer. But then the thin layer of viscous fluid may have little influence on the instability of a fluid, just as in the fracture of a solid where localized plasticity is known to have a negligible effect on the critical load. It thus appears that the inviscid flow around a solid body coupled with a criterion of separation may provide sufficient information to forecast separation. The criterion of maximum potential energy density* originally developed for the fracture of solid may be extended to flow separation and reworded as

> *Separation occurs at the location near the boundary where the rate of increase of potential energy density is a local maximum.*

Some insights into this statement may be gained by following a differential volume as it flows near a boundary. The momentum of the volume will decrease due to shear losses. It is the usual experience for flow along solid boundaries to have an adverse pressure gradient on the downstream side of the body. Momentum losses make it impossible for the material volume to overcome this steep potential energy barrier, and it is in this region that separation occurs[17]. Thus, it appears reasonable to anticipate that separation will occur where the potential energy barrier is the steepest. Since the potential energy expression cannot be determined analytically for many flows, it is easier to search for minima in the rate of decrease of kinetic energy (T) density. These are equivalent to the maxima in the rate of increase of potential energy (V) density as a result of the conservation of energy which can be written (using the super dot to denote the derivative with respect to time) as:

$$\dot{T} + \dot{V} = 0 \tag{7}$$

The minima of $\dot{T}$ for several shapes of solids in a potential field have been obtained. The results for a circular and narrow elliptic cylinder will be discussed.

When a uniform flow-field passes a stationary circular cylinder, the theory predicts separation points at angles ±125.26° from the forward stagnation point. This is in total agreement with known experimental results that show separation occurring between ±122° and ±130° from the forward stagnation point[18]. As the cylinder rotates, the separation points tend to shift in the direction of rotation, as expected, until the rotation speed is so fast that the flow along the lower portion of the cylinder can no longer be established and only one separation point occurs. This physical situation was examined for laminar flow by Prandtl[19] whose results show the same behavior of the separation points as predicted by the $\dot{T}_{min}$ criterion. The theory predicts a narrower wake than Prandtl's, as would be expected for turbulent flow.

Another interesting case is the turbulent flow past an elliptic cylinder, Figure 10. An aspect ratio of L/D = 6 is depicted so that the results can be compared with the available data on airfoils. In the figure, the points of separation are located by θ_1 and θ_2 and β is the angle of attack. The numerical values of θ_1 and θ_2 for six different angles of β are given in Table 2.

Table II. Separation points determined by θ_1 and θ_2 for an elliptical cylinder with L/D = 6

β	θ_1	θ_2	β	θ_1	θ_2
2.0°	171.10°	-174.90°	7.0°	164.67°	-177.93°
3.5°	169.35°	-175.99°	8.0°	16.64°	-178.56°
5.5°	166.76°	-177.09°	12.0°	12.02°	179.68°

An important aspect of these calculations is the prediction of stalling defined as the point at which the wake suddenly increases in width causing a drop in the lift coefficient. For the elliptical cross section with L/D = 6, Table 2 shows a severe stalling at an angle of attack between 7° and 8°. Experimental studies on the R.A.F. 34 airfoil with that aspect ratio showed that stalling occurred in the range of 12° to 14° angle of attack[18].

**For a solid, this is equivalent to the minimum strain energy density criterion[4] discussed earlier.*

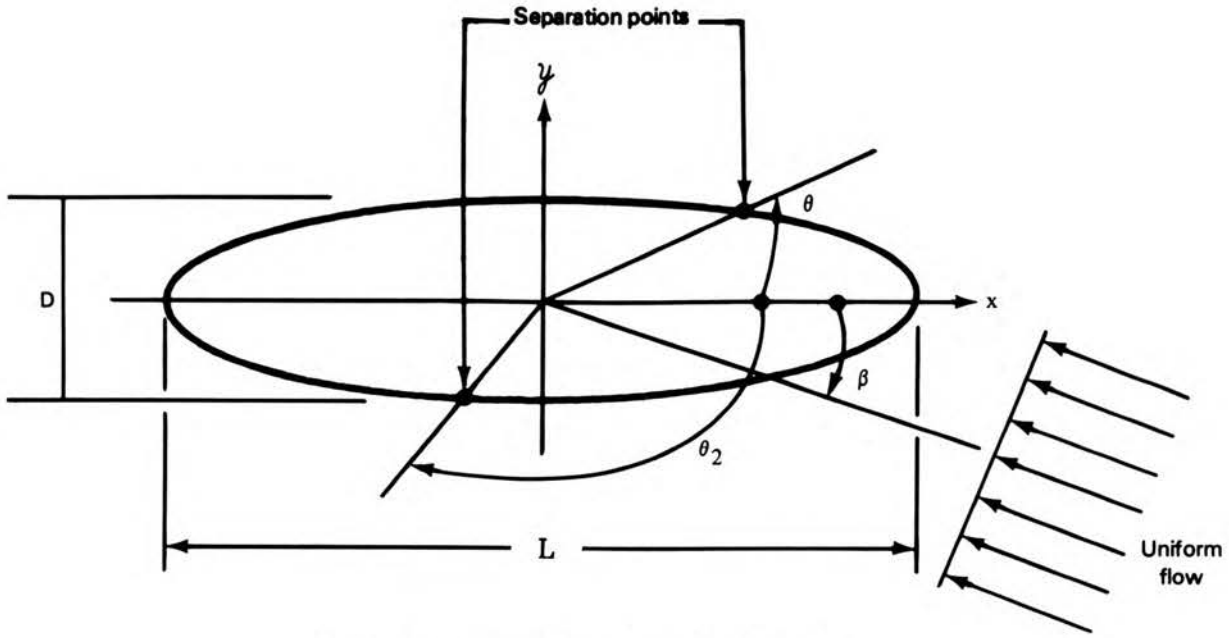


Figure 10. Flow past an elliptical cylinder with L/D = 6.

These results are consistent with those in Table II as the airfoil is designed to delay stalling as long as possible without a large increase in drag.

The prediction of external turbulent flow separation is a problem that has been extensively investigated in the literature. Many criteria for calculating two-dimensional separation points have been proposed and most yield reasonable results. However, all of them require tedious computations and experimental information that make them impractical for design use. There are relatively few methods for calculating three-dimensional turbulent separation points, and those that do exist are semi-empirical and yield marginal results[20].

The close agreement between T_{min} predictions and known experimental results is not coincidental. It is believed that this criterion will accurately predict two- or three-dimensional turbulent separation points on solid bodies with arbitrary shapes. The ease of calculation makes this procedure a very powerful tool for designing Navy vehicles.

What Lies Ahead

With the advent of large size computers, it is not inconceivable that the future design of large size structures will rely more and more on numerical and/or analytical calculations because full scale testing or modeling is a costly procedure. Basic research in this area should continue with increased intensity.

The mere computation of stresses and/or strains in a solid is not sufficient. Realistic and sufficiently general failure criteria should be incorporated into the analysis so that redesign of structural members can be accomplished very rapidly and economically on the computer.

The ductile fracture phenomenon of rapid crack propagation preceded by slow crack growth can be modeled in three-dimensions using the finite element method. The different increments of slow growth with changing crack front shapes have been predicted[15] by application of the strain energy density criterion. Incorporation of the effect of plasticity makes the analysis much more complex. Although the preliminary results are encouraging, accuracy of the finite element procedure still leaves much to be desired. There is no doubt that the size effect observed in ductile fracture is now understood and can be resolved. The time schedule will depend very much on future funding in this area of research.

The ability to control the path of crack propagation is a very useful concept. Large structures such as airplanes or ships should be designed so that they can release energy by stable crack propagation in a predetermined portion of the structure that is easily accessible for inspection and repair. Any attempts made to avoid the occurrence of cracks completely can lead to excessive constraint or to the use of high strength

material. The consequence of the latter could be disastrous because of the possibility of catastrophic brittle fracture.

A computer program should be developed to incorporate the $\dot{T}_{min}$ criterion for analyzing any three-dimensional body shape propelled through air or water or the combination of both. Such a program would allow the designer to determine the vehicle shape that will delay turbulent separation or reduce the size of the wake that can greatly decrease this portion of the drag. If this procedure proved successful, it could result in a significant reduction of cost as compared to the present-day design method. ■

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research notes

Submersible Alvin Makes 1,000th Dive

The Deep Submergence Research Vehicle *Alvin*, operated by the Woods Hole Oceanographic Institution, made her 1,000th dive on January 15, which also happened to be the 50th anniversary of the organization of the Institution. The three-person *Alvin* is a national research vehicle supported by the National Science Foundation (NSF), the Office of Naval Research (ONR), and the National Oceanic and Atmospheric Administration (NOAA). The sub's depth capability is 4,000 meters (13,124 feet).

Those participating in the 1,000th dive were *Alvin* Chief Pilot Ralph Hollis, NOAA Geologist Alexander Malahoff, and George Broderson, *Alvin* crew chief and veteran of 16 years in the sub's working group.

This was one of several dives for Dr. Malahoff's studies of volcanic processes at the intersection of the Ecuador Rift and two fracture zones, undersea mountain structures just north of the equator in the Pacific Ocean. The work also included examination of the origin and growth of several seamounts on the south flank of the Carnegie Ridge and erosional processes around the seamounts.

The nation's first research submersible, *Alvin* was constructed in 1964 under a Navy contract by the Electronics Division of General Mills (later the Applied Sciences Division of Litton Industries). The sub's usefulness for work on the sea floor was proven early when she participated in the search for and eventually located a hydrogen bomb lost in the Mediterranean off Spain following a 1966 plane collision.

Since that time, as pilots have become increasingly skilled at maneuvering the sub and a corps of experienced scientific users has assembled, the ratio of testing to working dives has moved heavily toward the scientific. *Alvin* began as an engineering dream with great potential and has become an important oceanographic tool much in demand.

Alvin coming into Lulu after a dive.

Major users of *Alvin* are biologists and geologists whose fields require considerable direct observation. Increasing sophistication of sampling devices has brought chemists into the user fold, and physicists have made current and other measurements using the sub. Work with *Alvin* has uncovered important new information on ocean bottom sedimentation and sediment movement and erosion, deep sea microbiology, communities of animals that live in the sediments, and distribution of animals in the water column. Long-term programs based on submersible work have included microbiological and sediment colonization research at bottom stations established at 1,830 and 3,660 meters (6,000 and 12,000 feet) and a series of expeditions beginning in 1974 aimed

at better understanding of the theory of plate tectonics, the idea that the surface of the earth is composed of huge crustal plates that are in constant very slow motion. A recent expedition to the Galapagos Rift was featured in the November 1979 issue of *National Geographic* magazine.

With the initial steel personnel sphere, *Alvin* could dive to 1,830 meters (6,000 feet). A titanium sphere installed in 1973 doubled the depth capability. *Alvin*'s early years were funded by ONR which owns the sub and sometimes employs *Alvin* for inspection of underwater structures. Beginning in 1974, the NSF and the NOAA agreed to share the funding with ONR.

Alvin is an elision of the two parts of Woods Hole Oceanographer Allyn Vine's name. Well-known as an innovative engineer, Vine is credited with firing the enthusiasm of Navy powers for building the sub and with participation in the craft's design. The sub's mothership, *Lulu*, a 105-foot pontoon vessel, is named for Vine's mother. ■

(Keith Kaulum, ONR)

Improved Hydrogen Maser Clock

With hydrogen maser clocks now routinely performing near the theoretical limit set by thermal noise, the devices have become the most accurate frequency standard available to science. At room temperature this performance corresponds to a stability of six parts in 10^{16} measured over one-hour averaging intervals. Such masers are currently being developed and built at the Harvard-Smithsonian Center for Astrophysics for very long base-line interferometry and satellite-tracking applications.

The prospects for further stability have been enhanced as a result of recent experimental tests with a cryogenic atomic hydrogen maser. Successful oscillation at temperatures down to 25°K was attained recently. This was made possible by the introduction of carbon tetrafluoride into the supercooled maser cavity, where it froze on the cavity walls to form a surface similar to that of the Teflon walls used in room-temperature masers. This coating successfully preserved the phase of the oscillating hydrogen atoms as they collided with the cavity walls. At a temperature of 30°K the available stability of oscillation was calculated to be below one part in 10^{16}, a factor of six better than the hydrogen masers currently in use.

Work is now under way to obtain oscillation at 4°K, with the stability expected to below one part in 10^{17}. Frequency stability in this range could have considerable interest for the development of Doppler spacecraft tracking techniques for detecting very low frequency gravity waves and other tests of gravity theories.

This work is being pursued at the Harvard-Smithsonian Center for Astrophysics by Robert Vessot, Eric Blomberg, and Edward Mattison with support by ONR. (Article from *Transactions, American Geophysical Union 60*, July 17 (1979). Other aspects of this work were reported in the June 1979 ONR Monthly Highlights.) ■

(Ted G. Berlincourt, ONR)

Electrochemical Polymerization on Graphite Fibers Developed

A project concerning electrochemical polymerization on graphite fibers has been completed at Washington State University under the direction of Professor R.V. Submaranian. The primary objective of this investigation was interphase modification in graphite fiber composites by polymer coating of the reinforcing fibers, prior to composite fabrication, by electrochemical techniques.

The investigation developed techniques of electropolymerization on graphite fibers. The occurrence of polymer grafting to the fibers was established. Indications were obtained of the influence of the graphite fiber surface on the stereochemical configuration of poly(methyl methacrylate) formed electrolytically on the fiber. In addition to vinyl polymerization, a number of novel electropolymerizations, previously unreported, were found to occur. These were investigated to establish the mechanism of electropolymerization and the structure of the polymer formed. The electroinitiated polymerizations of aziridines, benzonitrile, phenylacetylene, and 3-aminophenylacetylene belong to this group; for the first time the occurrence of electropolymerization through the opening of the cyclic functional group, aziridine, and of C≡N and C≡C bonds was established.

The properties of composites prepared from the polymer-coated graphite fiber were studied. The effect of the interphase polymer was found to be manifested in modification of interlaminar shear and impact strengths. The formation of interphase polymer by electrodeposition of ionizable polymers