Lawrence Berkeley National Laboratory
Recent Work

Title
A REVIEW OF LIWUID HYDROGEN SAFETY FOR RESEARCH EQUIPMENT

Permalink
https://escholarship.org/uc/item/7fd263mp

Author
Hernandez, H.P.

Publication Date
1966-06-02

eScholarship.org Powered by the California Digital Library
University of California

UCRL-16730

University of California

Ernest O. Lawrence Radiation Laboratory

A REVIEW OF LIQUID HYDROGEN SAFETY FOR RESEARCH EQUIPMENT

TWO-WEEK LOAN COPY

This is a Library Circulating Copy
which may be borrowed for two weeks.
For a personal retention copy, call
Tech. Info. Division, Ext. 5545

Berkeley, California

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Submitted to
Advances in Cryogenic Engineering

UCRL-16730
Preprint

UNIVERSITY OF CALIFORNIA

Lawrence Radiation Laboratory
Berkeley, California

AEC Contract No. W-7405-eng-48

A REVIEW OF LIQUID HYDROGEN SAFETY FOR RESEARCH EQUIPMENT

H. P. Hernandez

June 2, 1966

A REVIEW OF LIQUID HYDROGEN SAFETY FOR RESEARCH EQUIPMENT*

H. P. Hernandez

Lawrence Radiation Laboratory
University of California
Berkeley, California

June 2, 1966

ABSTRACT

Over ten years' experience with the use of liquid hydrogen in research apparatus related to large particle accelerators is reviewed. The long, continuous experience has provided some definite safety philosophies and design and operational procedures by accelerator laboratories.

Effort is made to approach safety through system safety and reliability. Consideration is given to equipment and facilities that make unsafe operation difficult. Many safety problems have been solved but many remain unsolved, particularly in the area of basic assumptions and quantities.

---

*Work done under the auspices of the U.S. Atomic Energy Commission.

A REVIEW OF LIQUID HYDROGEN SAFETY FOR RESEARCH EQUIPMENT

INTRODUCTION

This discussion is limited to the review of safety practices for high-energy physics research equipment filled with liquid hydrogen or deuterium. This equipment includes bubble chambers and targets, whose capacities vary from 10 to 1400 liters. A 12-ft-diameter bubble chamber is now under construction, and a 14-ft-diameter chamber has been proposed.

Design

The first safety problems were associated with the design of equipment. These problems included understanding the behavior of the equipment during normal and emergency conditions, specifying the cryogenic system, and satisfying the requirements of the experiment. To design the apparatus, more knowledge about the low-temperature properties of materials became urgent; this needed information was supplied by the National Bureau of Standards Cryogenic Laboratory in Colorado.

Operation

Together with the design came the first operating procedures, many of which are still followed.[1]

Installation

The next problem was how to safely install liquid hydrogen apparatus adjacent to other electrical research equipment. The emphasis was on the elimination of ignition sources. About the same time, the large bubble chamber with its separately isolated buildings was built with a crude attempt at system safety engineering.[2]

Management

With today's large and complex experiments came the need to arbitrate safety questions and to balance the scientific value of an experiment against its risks. To resolve these questions, the larger laboratories have adopted a high-level safety committee composed of representatives from science, engineering, and management. Management has the most important responsibility in safety through its difficult task of apportioning funds among scientific and support groups. The relative strength of the safety program is determined at this level.

Safety may also be specified in the contract such as Mil-S-38130[3]; then the motivation for management to support safety is built in and a common safety objective exists throughout the organization.

THE BASIC QUESTIONS

Before establishing a safety system it is necessary to specify the magnitude of the worst accident that the system is expected to prevent. This is the same containment problem that flood-control-dike builders have faced for centuries and the most difficult. It has also been known for a long time that those who apply the knowledge they have are far more successful in solving the problem than those who ignore it.[4] We may determine the necessary safety program by asking:

1) Can a catastrophic accident be contained by the safety system? The answer is no, but a safety system can be designed that will reduce the probability that a catastrophic accident will occur.
2) What is the most credible accident?
3) What accident severity shall we specify as an objective? To find the answer, we can weigh the cost of the system safety program against the cost of accidents. But this optimum cost is difficult to find. The cost

of system safety is definite but the cost of accidents, their number, and injuries caused by them are not definite and can vary widely. We decide on the amount of insurance believed necessary, then design the safety system to prevent the accidents implied by this standard. Be realistic--do not create an unnecessarily costly system, but do not deviate from the safety specification.

4) What margin of safety will the system safety program need to ensure that the specified safety standard will be satisfied?

These ideas are shown qualitatively on Fig. 1. The four zones indicate accidents of different severity--catastrophic, critical, marginal, and safe--and are defined in Ref. 3. The curve "Severity of Accidents to be Prevented" represents the specified standard of safety, or the operating value to be maintained; accidents less severe than those below this curve are to be prevented. Although this curve is arbitrarily shown in the critical zone, it can be positioned wherever you choose. To ensure that the specified safety standard is maintained requires that some safety factor be applied to the standard. The result is represented by the curve "Design System Safety to Prevent Accidents of This Severity." This curve can be thought of as a design value. Safety effort ("intrinsic safety effort," Fig. 1) never reaches zero because of everyone's self-preservation instinct.

SYSTEM SAFETY

System safety engineering is described in Ref. 3 as "the specific application of management, scientific and engineering criteria, principles and techniques in applicable disciplines throughout all aspects of system development to assure optimum safety." The concepts of system safety are described very clearly in Ref. 5.

Most large design groups of experimental apparatus now employ the concepts of system safety and integrate safety into the design from the beginning. System safety has also been used successfully by support groups that provide experimentalists with complete hydrogen targets. At some laboratories the support group even operates the equipment. The target group system was originated to ensure that only safe targets would be used. It was realized that to make the system work, it must be easier for the scientist to use a target system supplied by the target group rather than a target built by the scientist himself.

When a new target experiment is proposed, it is important that representatives from all groups involved meet during the conceptual stage to discuss the complete system. An early meeting results in a more reliable and safe system for the same amount of money to be spent and has led to better and faster installations. Also, by getting together early, the "my guys against your guys" syndrome is avoided. The object is to satisfy the experimenter and to optimize safety.

Maintainability is also very important,[6] particularly maintenance that ensures the reliability of seldom-used equipment such as flammable gas detectors.

SAFETY AND RELIABILITY

Safety can be enforced by edict, in which case safety must be enforced, or safety can be approached through reliability. Although this latter approach is indirect, it can be employed in a situation where safety is tolerated by a user group, and the safety group is advisory. One such situation is where there are many small, highly technical and separated hazardous areas.

How safety and reliability approach each other is illustrated by the sequence on Fig. 2 (a, b, c).

On Fig. 2(a) the sets Safe and Unsafe do not intersect because a system is either Safe or Unsafe. Similarly a system is either Reliable or Unreliable. But a system can be both Safe and Reliable, as shown by their intersection. The intersection of the Safe and Unreliable set is acceptable to only the safety group. However, a delay in operations caused by unreliability is corrected by the project personnel without question because their whole technical existence depends on a successful project. The converse occurs in the intersection of the Reliable and Unsafe sets, where the burden of correction falls to the safety group. The intersection of the Unreliable and the Unsafe sets is unacceptable to both groups, and thus both work to reduce this area.

An intermediate step is shown in Fig. 2(b) where the Unsafe-and-Unreliable intersection is eliminated and the Safe-and-Reliable intersection is increased. Finally, to make the set compatible for safety and reliability, we rearrange the sets as shown on Fig. 2(c). The common interest area is the Safe-and-Reliable intersection which both the safety and reliability groups accept. The Unsafe set is rejected by the safety group, and the reliability group may be indifferent to this set. The converse applies to the Unreliable set. Safety is now integrated into the program, the efforts of the reliability group and the safety group complement each other, and their efforts are in the same direction. I have attempted to show how two different disciplines having different objectives can arrive at a system completely acceptable to both.

OTHER PROBLEMS

Safety efforts are also blunted by natural pressures such as the great urgency to use the accelerator beam efficiently. Consequently, great enthusiasm and pressure are exerted to complete experimental apparatus and to keep experiments and the accelerator in operation. Experiments, by their nature, do not last very long and the experimental setups constantly change. Many experiments imply many safety judgments and thus result in a greater opportunity for errors, particularly errors of omission. Paradoxically, a good accident history also increases the pressure to reduce the safety standards, even though it was these very same standards that produced such a good safety record.

FUEL, IGNITION, AND VENTILATION

With the hydrocarbon fuels we are accustomed to the traditional fire triangle of fuel, oxidizer, and ignition; this concept carried over to the use of liquid hydrogen is in principle correct. But the following truth is emerging very clearly to all hydrogen users (whether in missiles or accelerators). Because liquid hydrogen released suddenly into air has so often ignited spontaneously, we should assume it will ignite every time. Consequently it is even more important to re-emphasize the design philosophy of containment of liquid hydrogen in experimental research apparatus.

The fact that the sudden loss of hydrogen may ignite spontaneously does not mean that ignition sources in the hazardous area are less important. It means instead that another problem has been added. Ignition sources still must be eliminated in the hazardous area to prevent any hydrogen leak from igniting. The methods available to eliminate ignition sources have not changed and are:

1. Remove the ignition sources.
2. Purge them.
3. Enclose them in an explosion-proof housing.
4. Apply the intrinsic safety principle to them.
    a. Limit the ignition energy.
    b. Isolate the sources.

The equipment enclosure must be ventilated to avoid a hazardous build-up of an explosive mixture of hydrogen. Also, the amount of combustible material around hydrogen equipment must be minimized to prevent a small burning hydrogen gas leak from escalating a small incident and thus create a catastrophe.

CODES AND RECOMMENDED PRACTICES

The use of a code does not guarantee success. A standard code represents a certain selected standard of safety for specific equipment. Anyone using it should understand it and know what degree of protection is intended. The earliest codes were written "after-the-fact" but today, through system safety engineering, the aim is to write the code "before-the-fact."

Each supplier or user of liquid hydrogen equipment has different safety needs and uses a code differently. A manufacturer of intrinsically safe electrical equipment must test the equipment component by component, as compared with a laboratory that builds one-shot and one-of-a-kind experimental apparatus and that tests only the most critical components. An organization frequently exposed to law suits will be motivated to use a code for legal protection rather than safety. A code may be specified in a contract or written by the user. But no matter what the situation, the first step in seeking a suitable set of safety rules is to define your own problems and form some ideas about their solution. Then, as a guide, apply all the applicable codes and see how your ideas compare with them. Remember that although all of the codes may not have been written for your specific problem the concepts are useful. After this you will know your own system better and have probably found a large gray transition area where the judgment is up to you. You also have a responsibility to see that an inapplicable code is not imposed upon you by a conscientious, over-extended authority.

Many disciplines have been solving the liquid hydrogen safety problem independently. To take advantage of these experiences, solutions to problems, and expensive tests, greater contact is needed over an even wider range of liquid hydrogen disciplines. In this connection, professional societies might improve their contacts with each other.

In addition to the safety sessions held at the Cryogenic Engineering Conference, there are also System Safety Sessions held at the American Institute of Aeronautics and Astronautics annual meetings. A System Safety Symposium, sponsored by the University of Washington and the Boeing Aircraft Company, was held in 1965 and another is proposed for 1967. The Instrument Society of America, which holds sessions on safety periodically, has made notable contributions to intrinsic electrical safety.

The following list of established codes and recommended practices may be helpful.

Codes and Recommended Practices

1. National Fire Protection Association National Electrical Code, Article 500, Hazardous Locations.
2. American Petroleum Institute, API RP-500. API recommended practice for classification of areas for electrical installations in petroleum refineries.

3a. Instrument Society of America RP-12.1. Electrical instruments in hazardous atmospheres.
  b. Instrument Society of America RP-12.2. Intrinsically safe and non-incendive electrical instruments.
  c. Instrument Society of America RP-12.4. Instrument purging for reduction of hazardous area classification.
4. ASME Boiler and Pressure Vessel Code, Section VIII, Unfired Pressure Vessels.
5. American Standard Code for Pressure Piping Sections (ASA B31.1 and B31.3).
6. Compressed Gas Association Inc. Pamphlet G-5.2T. Tentative Standard for Liquefied Hydrogen Systems at Consumer Site.
7. Liquefied Petroleum Gases 1963, National Fire Protection Association.
8. National Board of Fire Underwriters, FP File E20, Special Internal Bulletin No. 298, Particle Accelerator Installation - Fire Protection, 1 April 53.
9. Safety Engineering of Systems and Associated Subsystems and Equipment: General Requirements for Military Specification Mil-S-38130 (USAF) 30 September 63.

INSTALLATION AND OPERATION

An experimental hall associated with an accelerator is a heavy industrial-type building classified as nonhazardous--it is usually ventilated. Large bubble chambers are isolated in their own buildings, and are classified as Class I, Group B, Div. II in the National Electrical Code. Smaller hydrogen bubble chambers and liquid hydrogen targets are operated either inside the experimental hall or in an outside shelter. The area surrounding this equipment is usually classified as non-incendive, Class I, Group B, Div. II. A nonincendive device will not ignite a combustible mixture under normal operating conditions. When stray radiation can affect the experiment, the equipment is housed in a temporary concrete blockhouse.

A blockhouse is equipped with both natural and forced ventilation which discharges outside and above the experimental hall. Some consideration should also be given to controlling ignition sources around and above the blockhouse. The blockhouse provides a convenient way to control the hydrogen gas in the event of a very large accidental spill. However, the blockhouse is not gas tight and hydrogen gas can escape through the cracks.

A concrete blockhouse constructed at the Brookhaven National Laboratory for the 30-in. liquid hydrogen bubble chamber containing 240 liters is shown on Fig. 3. This blockhouse has a floor area of 26 ft by 23 ft, and is 28 ft high on the inside.[7] The blockhouse was designed for an overpressure of 5 psig based on the Bureau of Mines test at BNL.[8] The wall blocks are 4 ft thick and the roof blocks 2 ft thick. These dimensions were determined by the radiation requirements and the availability of the blocks. The blocks are held together with a structural steel frame tied together at the top with cables. Space above the roof blocks allows the blocks to lift.

At the Lawrence Radiation Laboratory, the inside of a different blockhouse of about the same size, and housing a liquid hydrogen target, is shown on Fig. 4. A view inside the Bevatron experimental hall is shown on Fig. 5; the concrete blockhouse in the center of the picture houses the 25-in. liquid hydrogen bubble chamber and is low to allow clearance for the overhead crane. The smaller blockhouse attached to it encloses the bubble chamber control room and is of heavy timber to protect the crew from neutron radiation. Figure 6 shows an inside view of the 25-in. bubble chamber in the same blockhouse.

When flammable-gas research apparatus is enclosed in a blockhouse, it isolates the hazardous equipment and the blockhouse boundary can be used to define the safety responsibility. Many laboratories hold the research group leader responsible both for the safe operation of his equipment and for the enforcement of the safety regulations. A secondary responsibility lies with the person in charge of the experimental building, who has the authority to shut down any experiment he believes to be unsafe.

A large bubble chamber operation is different again. It is more permanent and stable and usually has its own building and a permanent crew. A bubble chamber operation is similar to an industrial-process operation.

The hydrogen target operators may come from either the target group or the experimental group and may be technicians, students, or scientists. It is desirable to design the equipment so that its integrity is not dependent upon the person who assembles or operates the system. When the operator can depend on the system, he can focus his attention on the many small problems that usually arise during operation. That is, the exception principle can be applied. Beam windows should be thought of as rupture disks, as they are often the weakest part of the hydrogen vessel. Such windows should be clearly marked and personnel should not be permitted in front of them.

The need for a good operating procedure should be obvious. But it isn't. Almost every new user underestimates the complexities and the time required to turn on new equipment. The written operating procedure protects against the errors of omission and ensures that operations are performed in the proper sequence.[9] Writing the procedure gives the operating crew opportunity to review and learn their system, and to simulate and study fault conditions.

CONCLUSIONS AND RECOMMENDATIONS

In summary, this paper has reviewed some of the safety concepts that have been evolving over the past several years. The safety philosophy for liquid hydrogen experimental equipment for high-energy physics has, in general, been set; however, many old problems are still unsolved, and new techniques will create new safety problems.

Some specific points reviewed were:

1. Agree on the safety objectives, then design and implement a safety program to satisfy the safety needs.
2. Use the concepts of system safety. Continue to let safety be a design parameter and integrate safety into the project from the beginning.
3. Approach safety through reliability.
4. Emphasize again the containment of liquid hydrogen, the ventilation of enclosures for liquid hydrogen, and the elimination of ignition sources in hazardous areas.
5. Apply safety codes more carefully.
6. Maintain personal contact with safety groups that represent many disciplines.
7. Specify a boundary around liquid hydrogen equipment that can be used to clearly define the hazardous area and thus the safety responsibility.
8. Write and use a good operating procedure for liquid hydrogen apparatus in advance of hydrogen operations.

Some safety practices still differ among the laboratories, sometimes because the solutions were reached independently and there is little contact with other laboratories, and sometimes because of basic disagreement. Some of these problems are:

1. What quantity of liquid hydrogen and other flammable fluids should be permitted in an experimental hall?
2. Distance tables - how far to store liquid hydrogen from a building?
3. What design pressure should be specified for liquid hydrogen vessels and for their insulating vacuum tanks?
4. What is the size of the hazardous area?
5. How much safety is required?
6. When should hydrogen vent stacks be burned?

REFERENCES

1. C. Godfrey, R. A. Byrns, "Operating Procedures for Liquid Hydrogen Targets," LRL Unpublished Safety Procedure 95, 17 Nov. 1952.
2. J. D. Gow, "Development and Operations of Liquid Hydrogen Bubble Chambers," in Proceedings of the 2nd United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, United Nations 1958.
3. "General Requirements for Safety Engineering of Systems and Associated Subsystems and Equipment," Military Specification, Mil-S-38130 (USAF), 30 Sept. 63, U. S. Government Printing Office.
4. H. P. Hernandez, "Designing for Safety in Hydrogen Bubble Chambers," Proceedings of the 1956 Cryogenic Conference, Boulder, Colorado, Feb. 1957.
5. John L. Umlauf, "Case History/Minuteman/for Weapons System Safety," in Proceedings System Safety Symposium, University of Washington and Boeing Company, Seattle, 8 June 65.
6. De S. Coutinho, "Reliability and Maintainability," Mechanical Engineering, February 1966.
7. J. A. Bamberger, "Notes on 30-inch Blockhouse - Safety," Brookhaven National Laboratory, 6 May 66.
8. M. G. Zabetakis, A. L. Furno, and H. E. Perlee, "Hazards in Using Liquid Hydrogen in Bubble Chambers," U. S. Bureau of Mines Rept. 6309, 1963.
9. R. Reider, "Written Procedures," Health & Safety News Letter 62-7, Los Alamos, 27 August 62.

FIGURE CAPTIONS

Fig. 1. Accident severity - The probability of an accident decreases as the effective safety effort increases. A safety program can be designed to prevent accidents of severities other than the one arbitrarily selected for this figure.

Fig. 2. Safety and reliability. (a) The sets Safe and Unsafe do not intersect as something cannot be both safe and unsafe simultaneously. The same argument applies to Reliable and Unreliable. (b) Neither the safety nor the reliability groups can accept the Unsafe and Unreliable intersection; therefore, the sets have been rotated to eliminate this intersection and to strengthen the Safe and Reliable intersection. (c) Both the safety and the reliability groups have maximized the Safe and Reliable. Safety effort has eliminated the Reliable but Unsafe intersection. Reliability effort has eliminated the Unreliable but Safe intersection.

Fig. 3. Concrete blockhouse at Brookhaven for the 30-in. liquid hydrogen bubble chamber (courtesy J. Bamberger, Brookhaven National Laboratory, Upton, Long Island, New York).

Fig. 4. Liquid hydrogen target during installation. The target is located in a temporary building outside of the Bevatron. The liquid hydrogen target assembly holds about 30 liters in the reservoir and target and can be rolled in or out of the magnet.

Fig. 5. Bevatron experimental hall showing the 25-in. hydrogen bubble chamber blockhouse (upper center of picture).

Fig. 6. Inside the 25-in. bubble chamber blockhouse. The view is from over the top of the chamber expansion system.

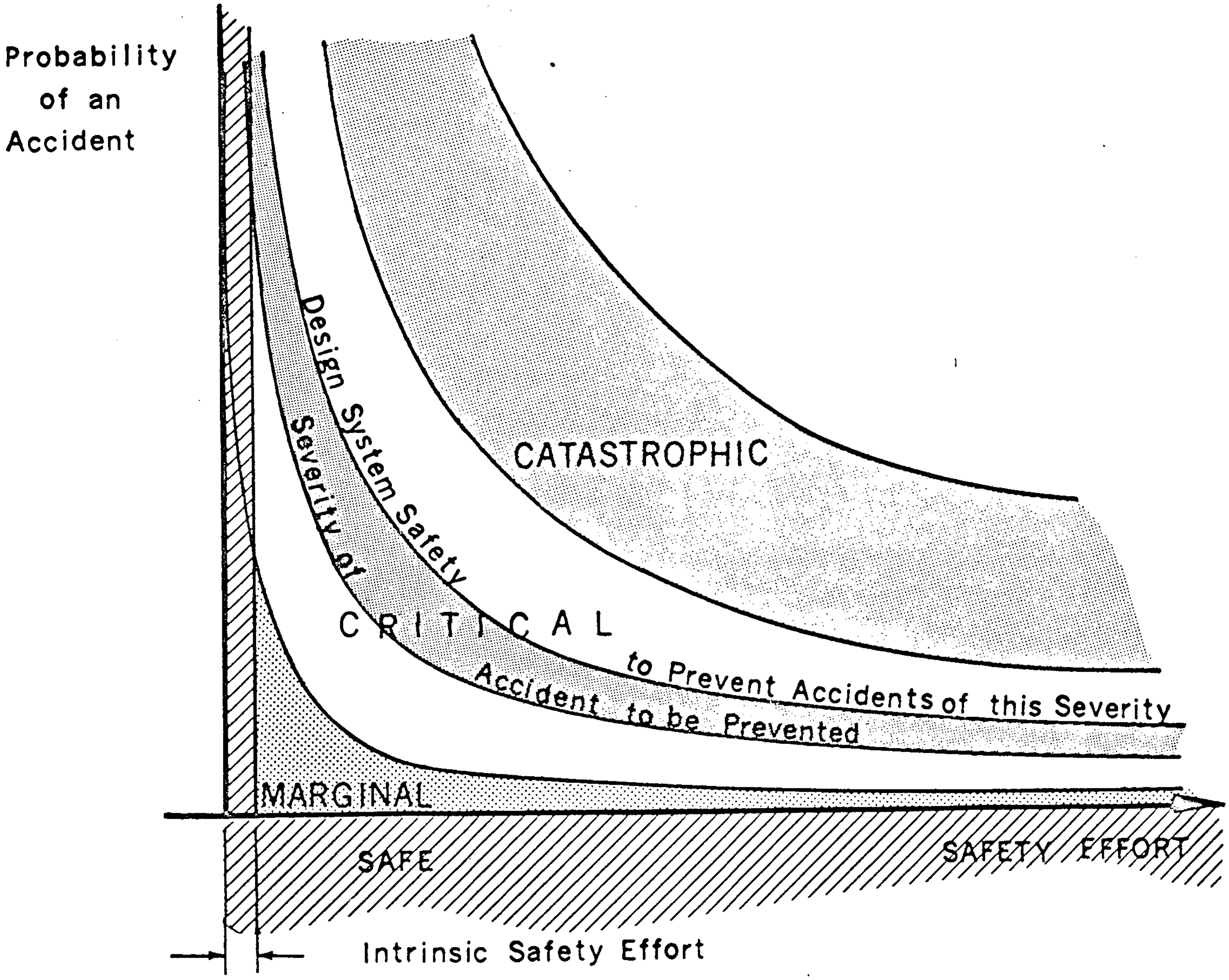

Probability of an Accident
CATASTROPHIC
Design System Safety
to Prevent Accidents of this Severity
Severity of
Accident to be Prevented
CRITICAL
MARGINAL
SAFE
SAFETY EFFORT
Intrinsic Safety Effort

Fig. 1

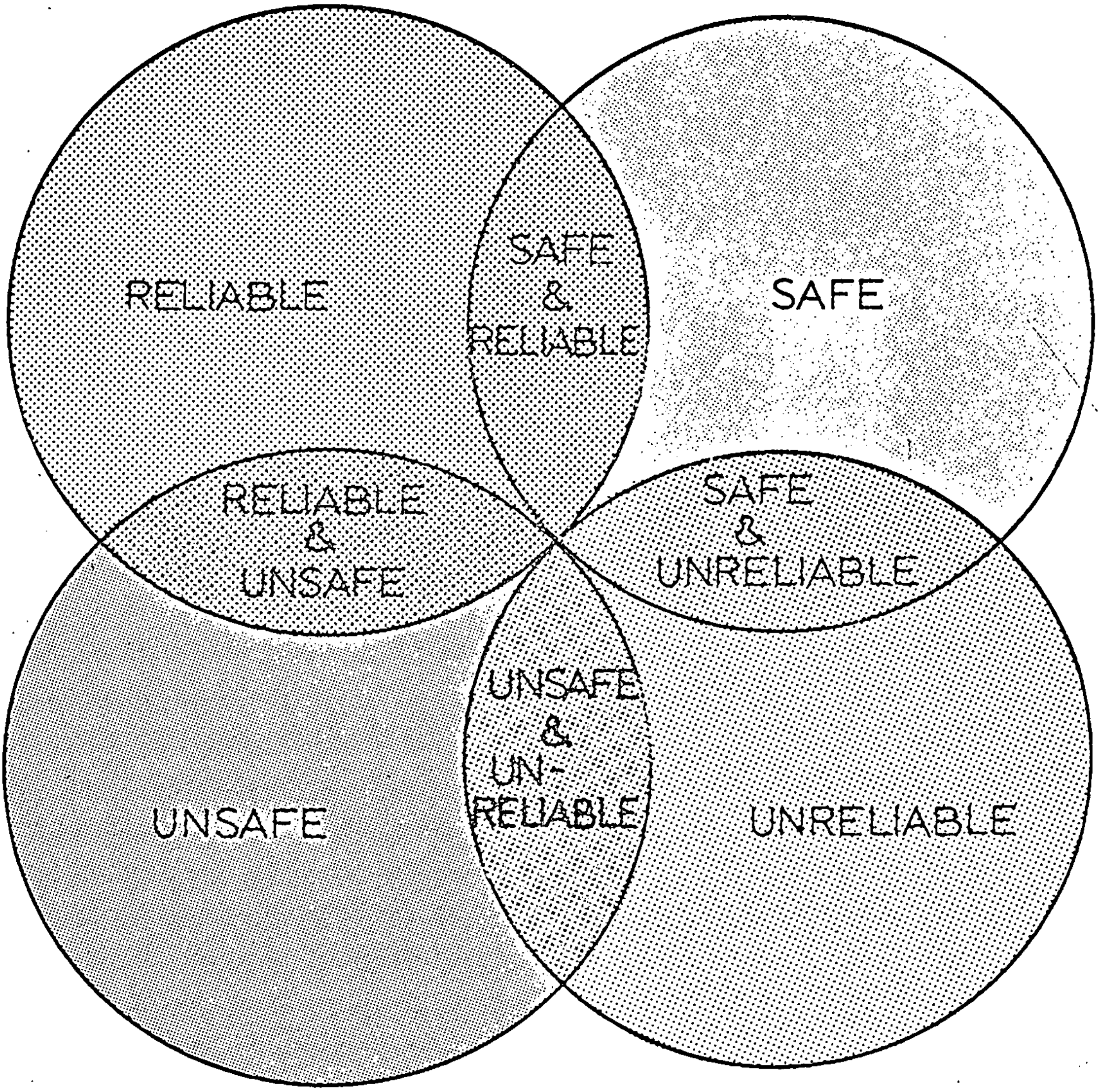

RELIABLE
SAFE & RELIABLE
SAFE
RELIABLE & UNSAFE
SAFE & UNRELIABLE
UNSAFE & UN-RELIABLE
UNSAFE
UNRELIABLE

Fig. 2a

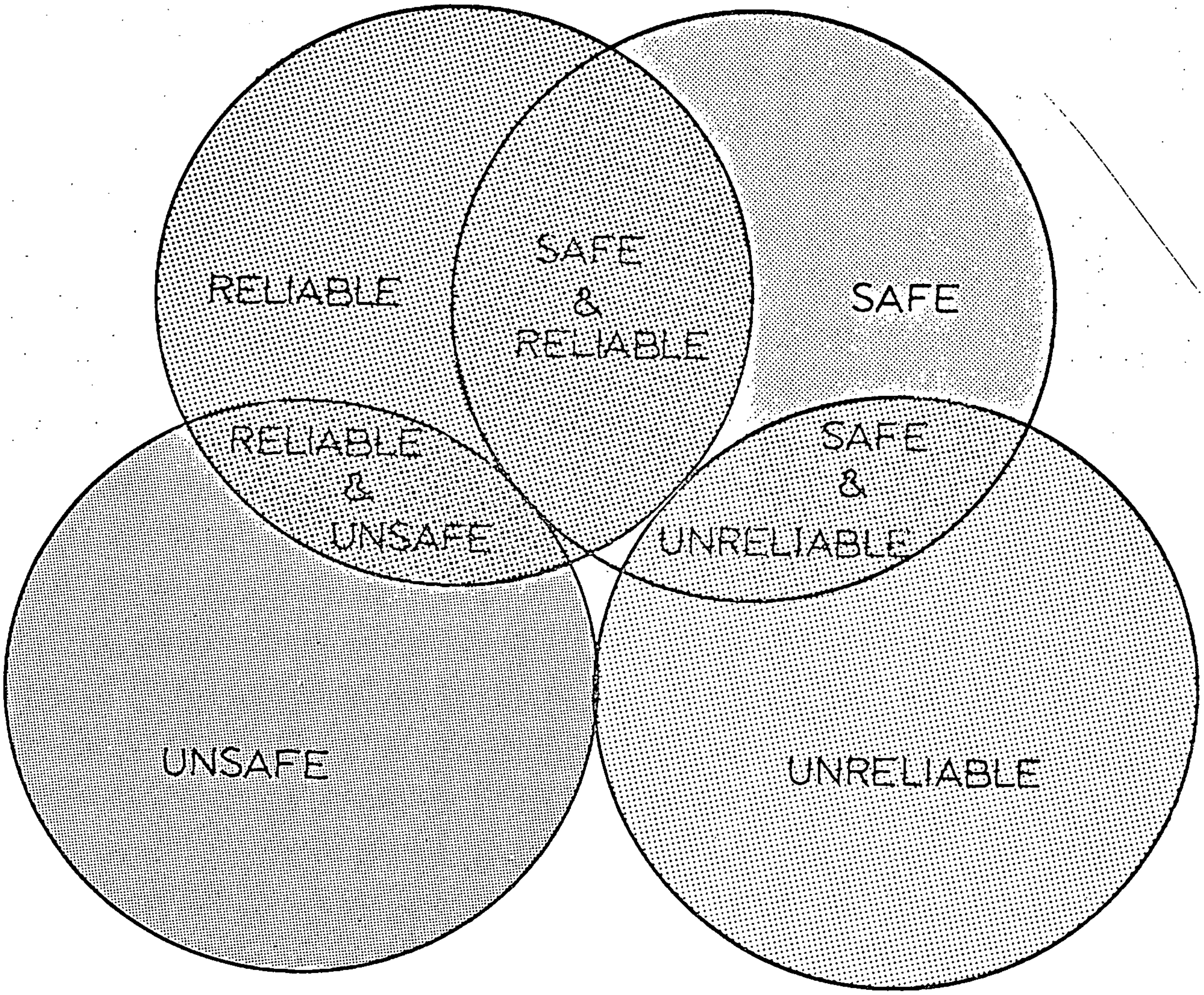

RELIABLE
SAFE & RELIABLE
SAFE
RELIABLE & UNSAFE
SAFE & UNRELIABLE
UNSAFE
UNRELIABLE

Fig. 2b

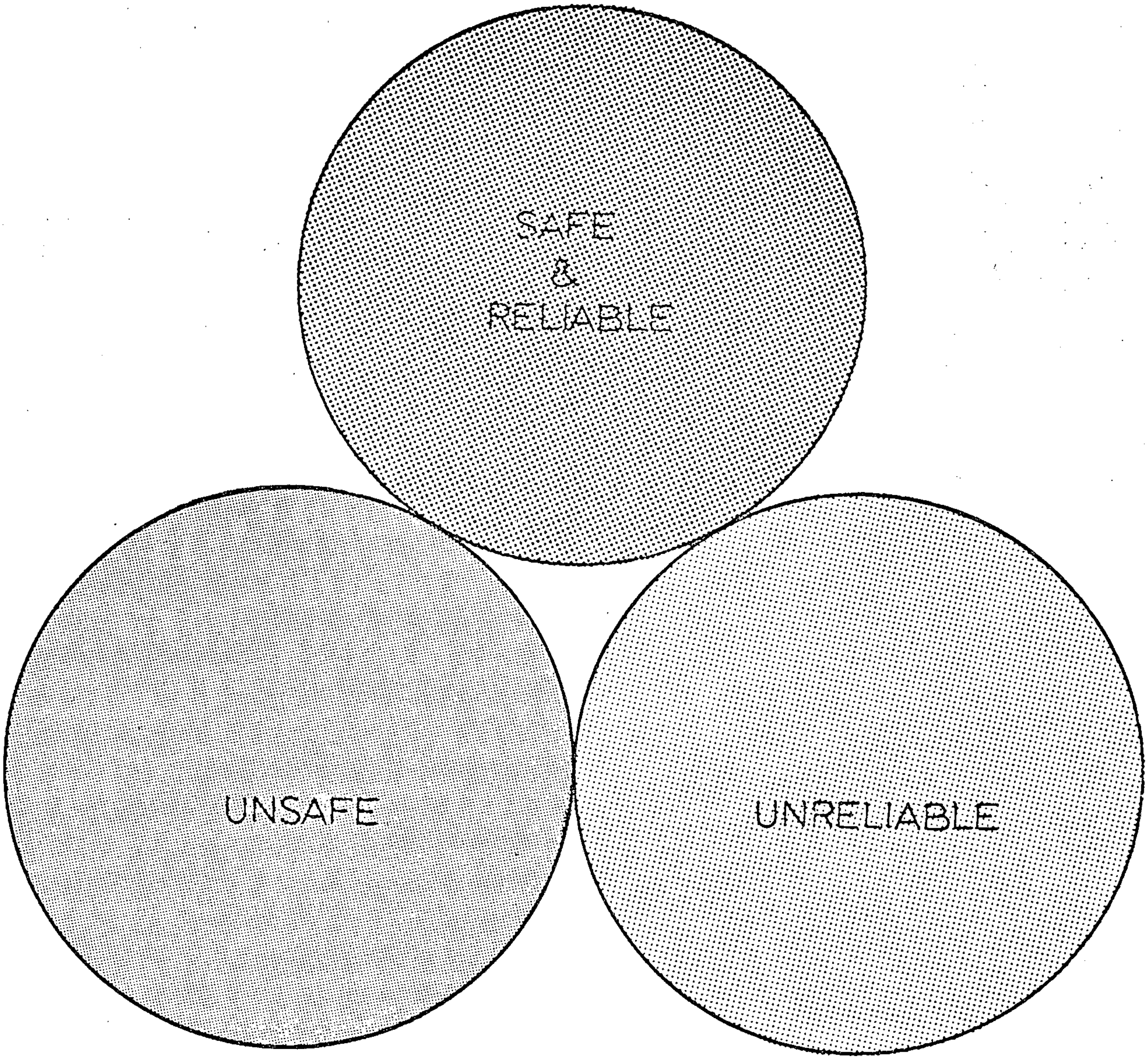
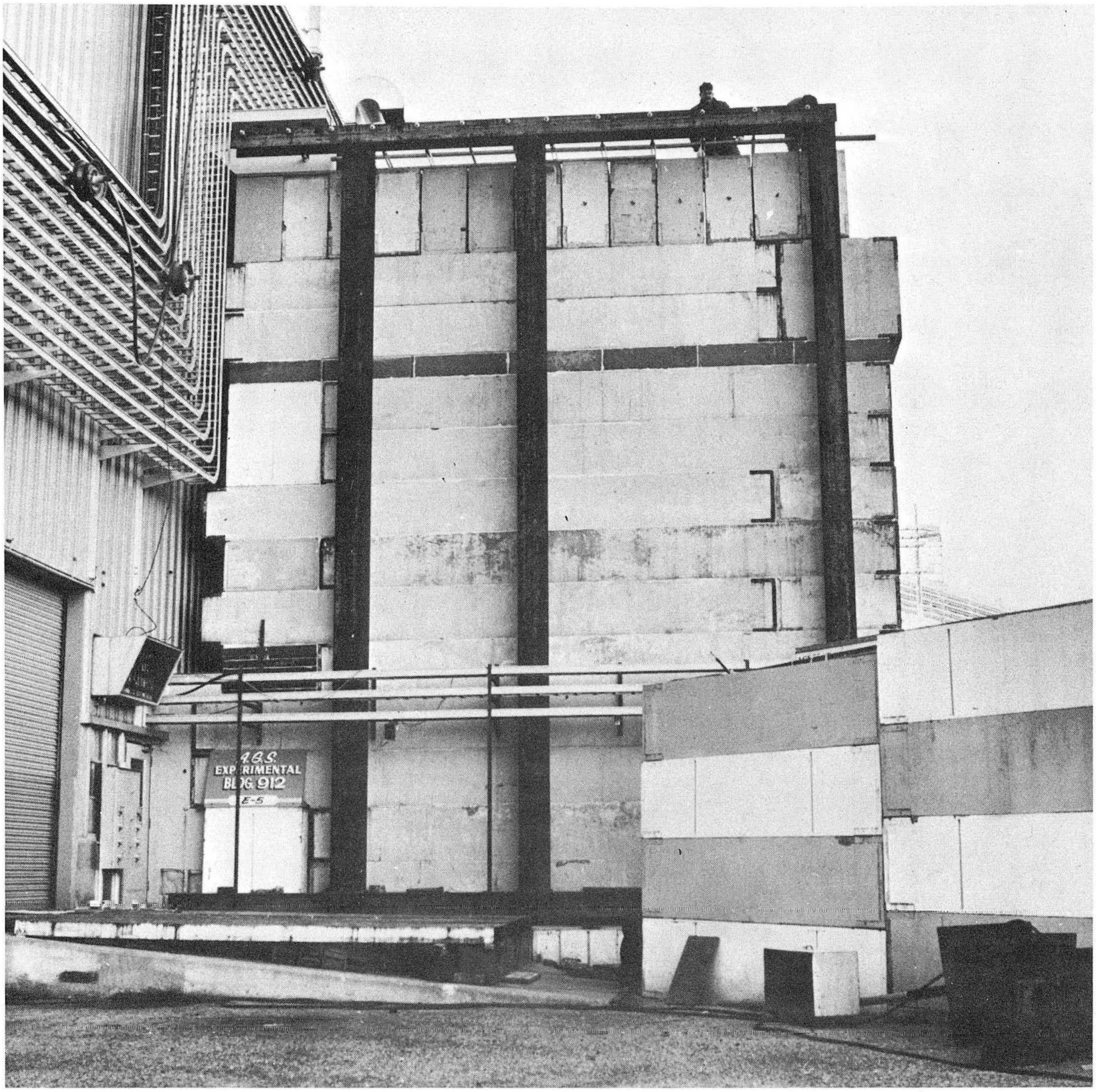
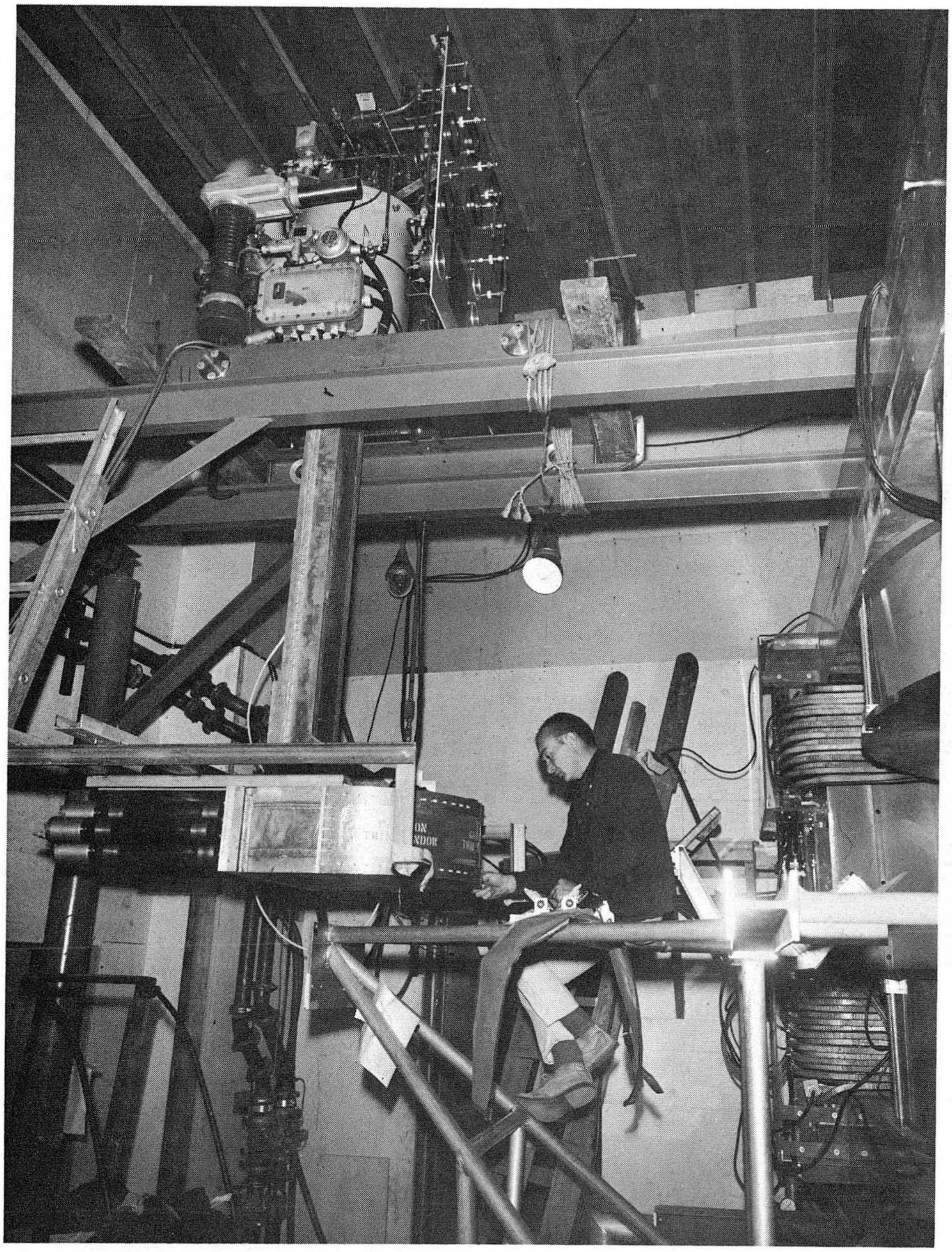


Fig. 2c



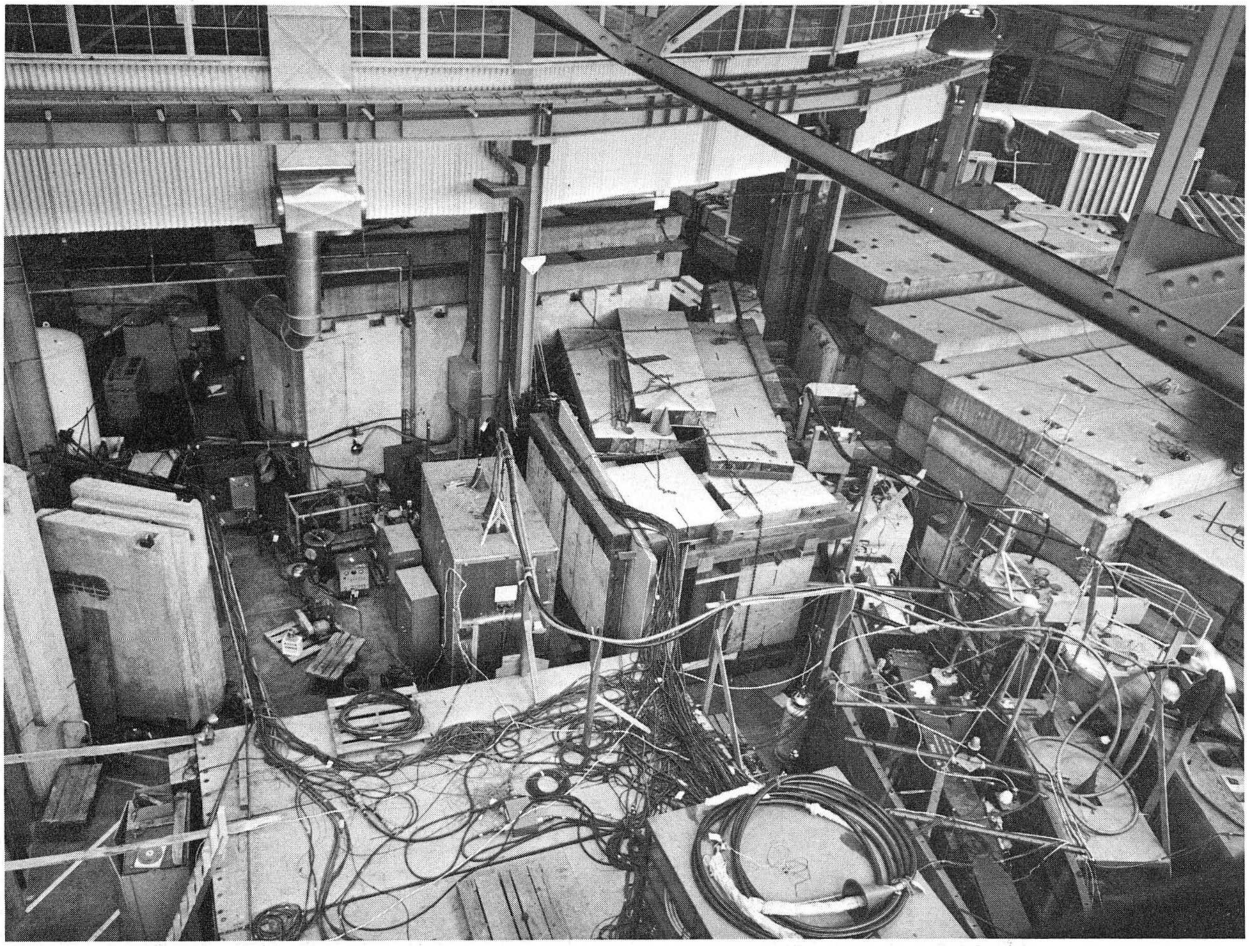
ZN-5517

Fig. 3



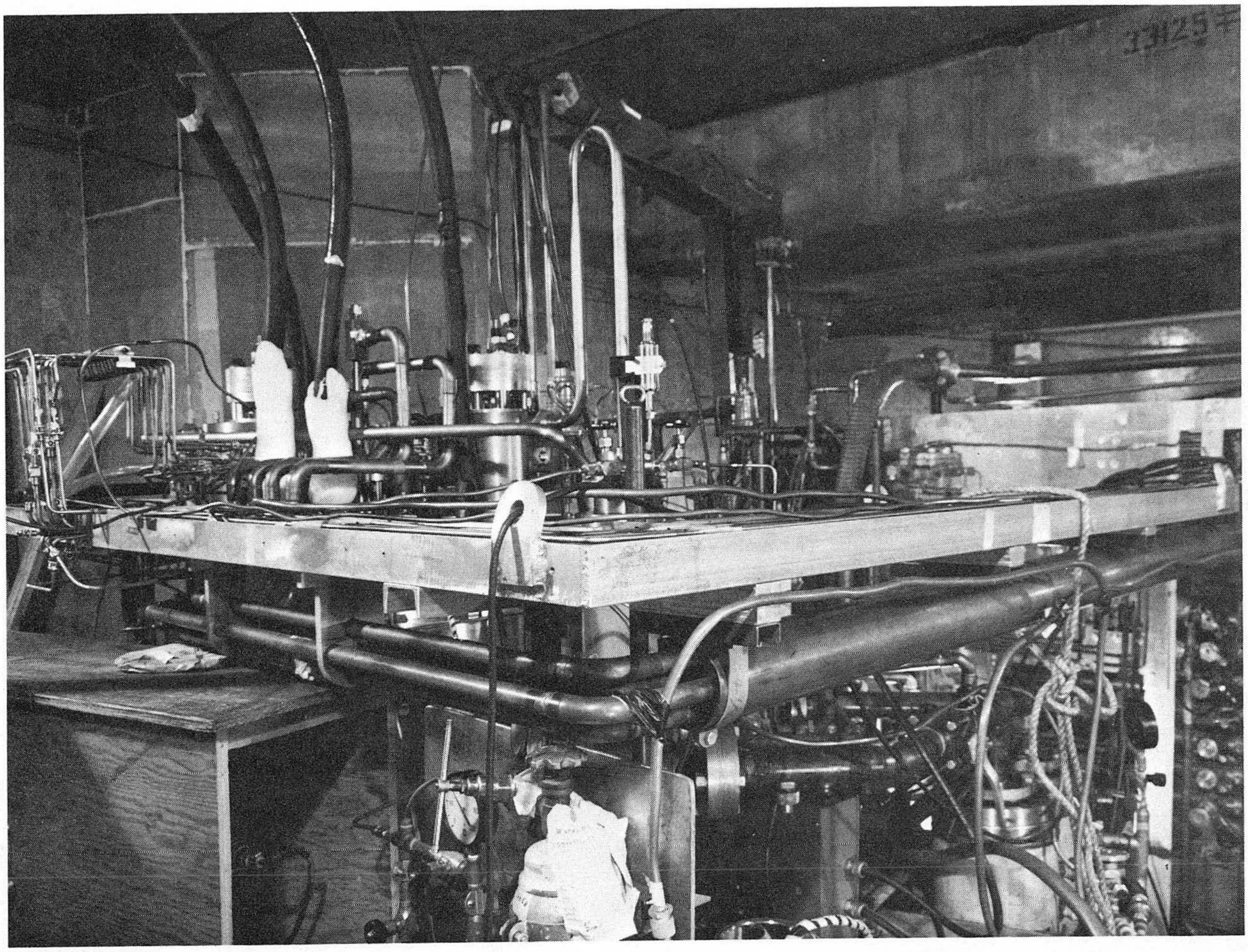
ZN-5518

Fig. 4



ZN-5519

Fig. 5



ZN-5520

Fig. 6

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.