2

CONF-8810184--1

OCT 04 1988

UCRL- 98542
PREPRINT

Structural Aspects of the Chernobyl Accident

Robert C. Murray
Garth E. Cummings

REPRODUCED FROM
BEST AVAILABLE COPY

This paper was prepared for submittal to
the Structural Engineers Association of California
SEAOC '88 Makahiki
Kailua-Kona
Big Island of Hawaii
October 4-9, 1988

September 2, 1988

Lawrence Livermore National Laboratory

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or 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 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. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Structural Aspects of the Chernobyl Accident[1]

Robert C. Murray
Garth E. Cummings
Nuclear Systems Safety Program
Lawrence Livermore National Laboratory
Livermore, California

UCRL--98542

DE89 001321

ABSTRACT

On April 26, 1986 the world's worst nuclear power plant accident occurred at the Unit 4 of the Chernobyl Nuclear Power Station in the U.S.S.R. This paper presents a discussion of the design of the Chernobyl Power Plant, the sequence of events that led to the accident and the damage caused by the resulting explosion. The structural design features that contributed to the accident and resulting damage will be highlighted. Photographs and sketches obtained from various worldwide news agencies will be shown to try and gain a prospective of the extent of the damage. The aftermath, clean-up, and current situation will be discussed and the important lessons learned for the structural engineer will be presented.

INTRODUCTION

This paper tries to draw together the design features and sequence of events that led to the Chernobyl accident. The audience is the practicing structural engineer, therefore, the emphasis is on structural features and not on the physics of the system. In preparing this paper many excellent reports were reviewed which provide very detailed discussions of the RBMK-1000 (the class of reactor to which Chernobyl Unit 4 belonged) design features and the operator actions and sequence of events that led to the accident. (See list of references at end of paper.) In reading these studies, each gives a slightly different discussion of the individual events leading to the accident.

Both the Soviets and independent investigators are still not sure what happened at Chernobyl on April 26 or of the actual sequence of events that led to the accident. However, enough is known so that important design deficiencies in the RBMK-1000 and lessons on human performance and administrative procedures have been identified. Most of these lessons are not new and were either a part of the U.S. Nuclear Power Program or incorporated into it after the Three Mile Island accident which occurred in 1979.

As with all accidents, important considerations are identified that can be used to improve the quality of our facilities. These must be used during the design process and properly balanced with other factors to further improve the safety of hazardous facilities.

---

[1] Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

LOCATION

The Chernobyl Nuclear Plant is located about 120 km north of Kiev, a major city of 2.5 million people in the Ukraine Region of the western part of the U.S.S.R. The site was named after the small town of Chernobyl, population 12,500. The nearest town is Pripyat, a community of 45,000 people 3 km away from the plant site. There were four Soviet RBMK-Type reactors in full operation and two more well into construction at the time of the accident. Fig. 1 shows the location of the plant with respect to Europe and the area nearby the plant site is shown in Fig. 2.

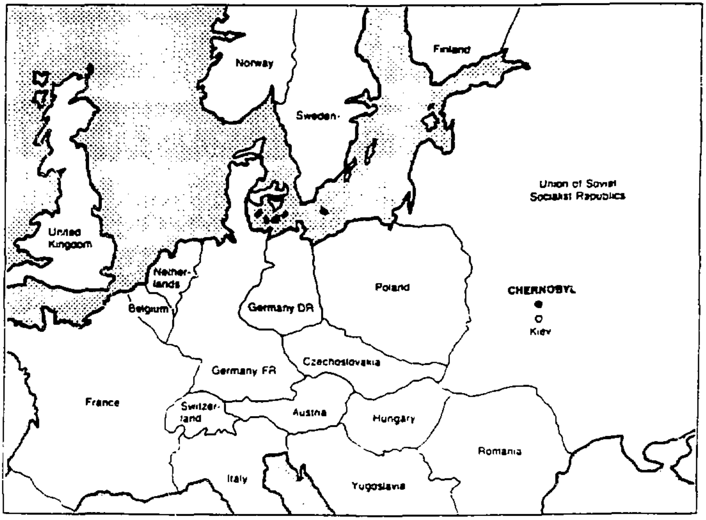

Fig. 1 Chernobyl reactor location (Snell and Howieson, 1986).

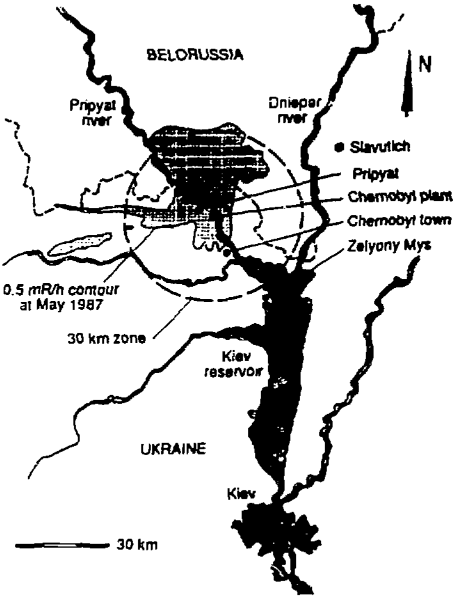

Fig. 2 Area nearby the Chernobyl reactor site (Rippon, 1988).

PLANT DESIGN

Chernobyl Unit 4 is a RBMK-1000 boiling light-water, pressure tube, graphite moderated reactor. At full power the reactor generates 1000 megawatts of electricity (3200 MW, thermal), which is typical of the generating capacity of most U.S. Nuclear Power Plants.

Chernobyl did not have a containment building which completely enclosed the reactor and coolant pressure boundary as do all U.S. commercial light water reactors. Containment walls were provided around and underneath the lower half of the reactor, but the top half is essentially uncontained (except for the core pressure boundary) and surrounded by an ordinary industrial building. Fig. 3 shows the RBMK reactor and contrasts it to typical U.S. reactor containment buildings which are constructed of thick steel-lined concrete structures. The layout of the Unit 4 reactor and adjacent turbine hall is shown in Fig. 4. A cross-sectional view is shown in Fig. 5. The RBMK design evolved from the military plutonium production reactors and were first constructed when soviet technology did not permit construction of large steel reactor pressure vessels and concrete containment structures. Currently there are about 15 RBMK type reactors in this size range operating in the Soviet Union.

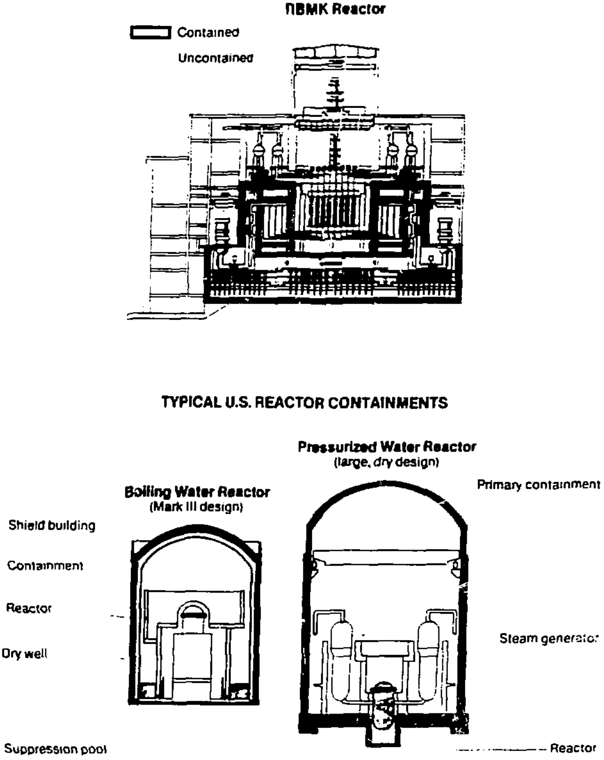

Fig. 3 RBMK reactor and typical U.S. reactor containment structures (EPRI, 1987).

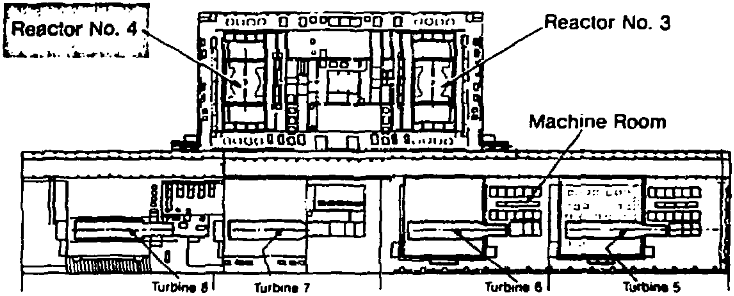

Fig. 4 Layout of main building of fourth unit of Chernobyl atomic energy station (Kouts, 1986).

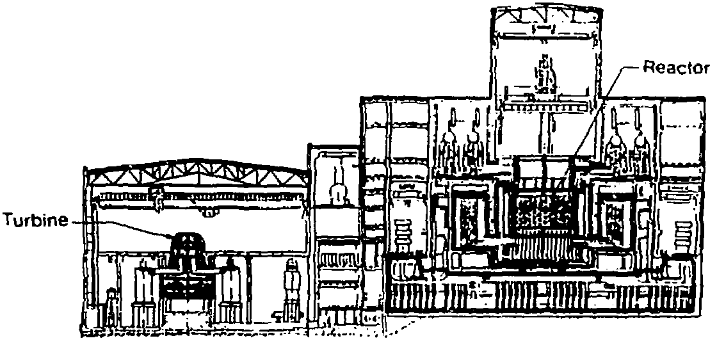

Fig. 5 Cross-sectional view of the main building of fourth unit at Chernobyl (Kouts, 1986).

The reactor core is composed of stacked graphite blocks (2000 ton) which contains the uranium fuel in 1661 pressure tubes each about 3 1/2 inches in diameter. Water flows vertically through these tubes to cool the fuel and generate steam to drive two turbine-generators. The pressure tubes are made of a zirconium alloy. The pressure tubes are connected by a series of pipes to four steam separators, which are large horizontal tanks used to separate steam and water. Steam is taken off the top of the separator to drive the two turbines. Water from the steam separators and turbines is returned to the reactors by pumps. The reactivity was controlled by 211 control rods which were hung from cables wrapped around electric motor driven drums. This control rod system is slow and can scram the reactor in about 20 seconds. An emergency cooling system was also available as a back-up safety system if the primary cooling system was not working. A schematic diagram of the reactor design is shown in Fig. 6. Partial containment was provided by reinforced concrete compartments surrounding various components. The core and pressure tubes were in a room with a capability to withstand about 26 psi. Suppression pools were located below the reactor to capture and condense steam from small pipe breaks but could not handle multiple pressure tube ruptures. The pressure capability of the industrial building over the reactor core has been estimated at 1/4 psi.

The reactor is unstable at low power and difficult to control, but achieves more stability at operating power levels. A rule existed that did not permit extended operation below 700 MW thermal.

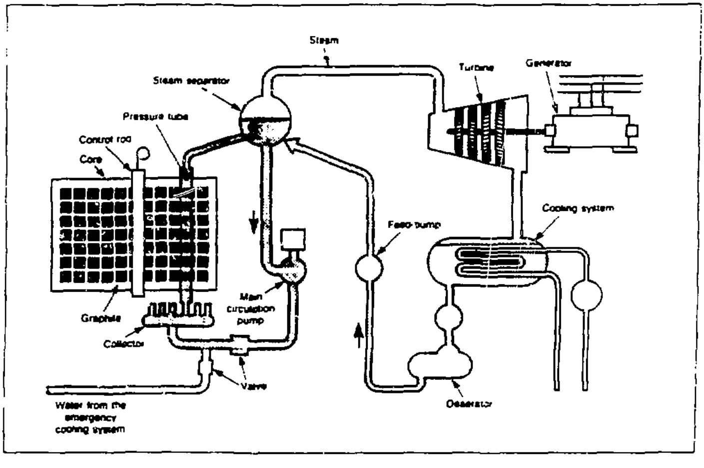

Fig. 6 Schematic diagram of the RBMK-1000 (Snell and Howieson, 1986).

ACCIDENT SEQUENCE

The accident took place during a planned experiment at the start of a normal maintenance shutdown. The test was to determine the ability to use electrical power from the turbine-generators as they coasted down during the first minute after loss of off-site electrical power. This would allow power to be supplied to essential components during the time necessary to bring the emergency diesel generators on line.

At 0100 on April 25 the reduction in power began as the start of the planned outage. (The sequence is shown in Fig. 7, each point being indicated by a letter.) Power was reduced slowly from the 3200 MW (thermal) operating level, (A, Fig. 7) to avoid damaging the fuel components. At 1300 the operating power had been lowered to 1/2 the normal level, (B, Fig. 7) and at 1400 a request to continue supplying power to the electrical distribution system was received. This postponed the test until the reactor was released at 2300, (C, Fig. 7). The reduction in power level then continued to the 700 MW (thermal), (D, Fig. 7), the lowest power level at which it was safe to conduct the test.[2] At this level, reactor control was switched to low power instrumentation. During this switch over, the operator neglected to signal the control system to hold power steady. The power level fell to about 30 MW (thermal), (E, Fig. 7) before the operator regained control and stabilized power at 200 MW (thermal), (F, Fig. 7). In violation of operating procedures, it was decided to run the test at this power level rather than shut down the reactor. Additional main circulation pumps were turned on and fuel water flow to the steam separators were adjusted. Additional safety circuits were locked out to allow the test to be conducted, (G, Fig. 7). Boiling in the reactor stopped. Further control rods were withdrawn to increase power. Feedwater flow was reduced and boiling began again in the core. Control rods were inserted to stabilize the reactor and turbine trip scram circuits were blocked. At 1:23 on April 26, the test began and a turbine was taken off line and began to coast down. The transport of heat from the reactor dropped and steam voids increased in the reactor, (H, Fig. 7). This resulted in increasing reactivity thus increased power and automatic insertion of control rods, however, reactor power was now above the normal operating level. The operators activated the scram button but additional control rods could not be inserted fast enough. At this time the power level was at about 100 times normal power. This increase in energy to the fuel caused pressure tubes to rupture. One second later there was a steam explosion, tearing the 1000 ton cover off the reactor core, breaking all pressure tubes, pulling out all control rods, and throwing hot fuel and graphite high into the environment. Hot debris falling on the roof started fires. Fire fighters from the site and the nearby towns fought the fire. They were hampered by high radiation, inadequate protective clothing, and lack of ways to get them and their equipment on the roofs. Through heroic efforts all fires except that in the core were out within 4 to 5 hours thus preventing spread of the accident to the other operating units. The 31 deaths directly linked to the accident were fire fighters and operating personnel. Figure 8 shows the reactor a few days after the accident. Significant damage to the concrete structures is evident.

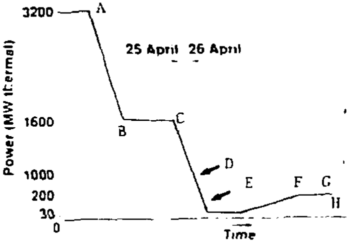

Fig. 7 Schematic diagram showing thermal power changes the day before the accident and the rapid change as the accident developed. Letters refer to events explained in the text.

---

[2] Regulations prohibited operation of the reactor below the 700 mw (thermal) level since the reactor becomes unstable.

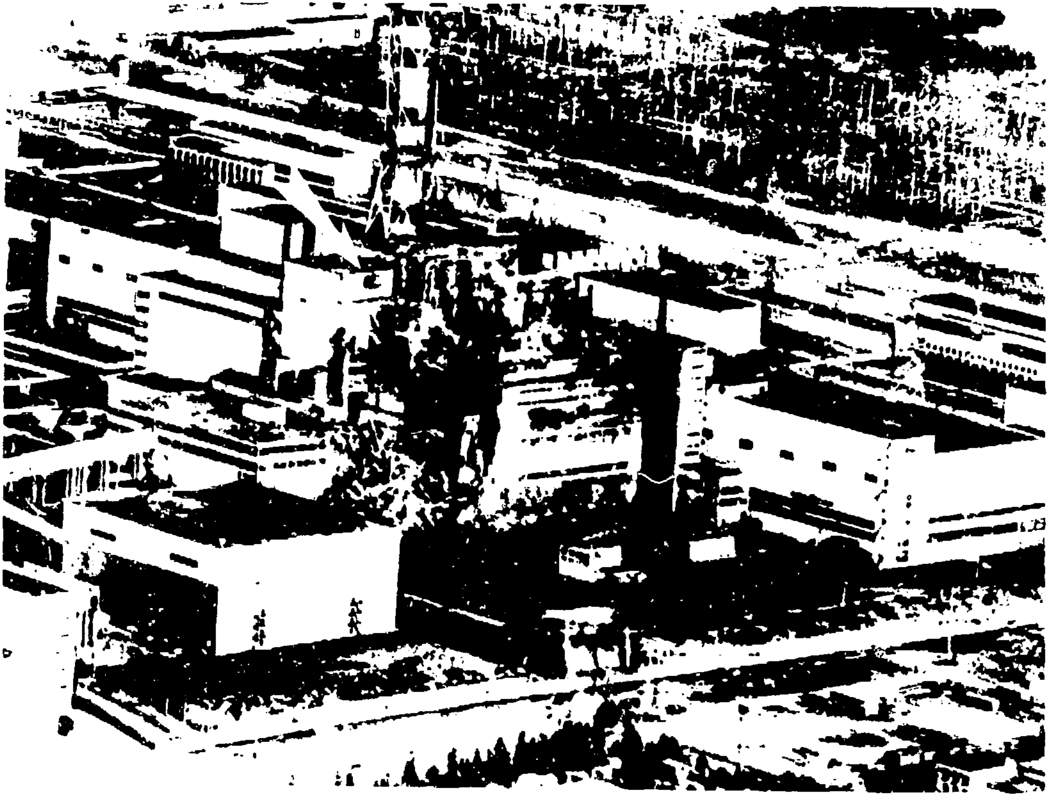

Fig 8 Damage to Unit 4 after the accident.

ACCIDENT MANAGEMENT AND CLEAN-UP

Emergency medical and radiation safety teams were sent from Moscow after notification that a problem existed. Inhabitants of Pripyat were told to remain inside their houses. They were evacuated the next day due to high radiation levels. About 135,000 people were evaluated from a 30 km radius around the accident site, (see Fig. 2). Emissions from the plant continued for the next nine days as the graphite core continued to burn. Estimates of daily releases are shown in Fig. 9. Emergency teams were dropping tons of lead, sand and clay, dolomite and boron carbide on the plant in an attempt to quench the burning graphite. After the fifth day the radioactive release started to increase. This was thought due to the insulating effect of all the material dropped on the core. Liquid nitrogen was pumped into the space under the reactor for additional cooling. Releases essentially stopped on the tenth day.

A permanent vault, called a sarcophagus, was built around the Unit 4 reactor and the turbine building as shown in Fig. 10. This huge containment structure was completed by November 1986. Design and construction of the sarcophagus represented a major structural engineering accomplishment that was completed in a short time. Essentially all of Unit 4 was entombed by this structure which included internal monitoring instrumentation. Up to a meter of top soil was replaced around the site.

Units 1 and 2 were put back on line by the end of 1986 due to the need for electrical generation. Unit 3 was up back on line in December 1987.

Construction of Units 5 and 6 was halted due to the major decontamination effort needed for clean up. The decision to restart construction is planned for 1990.

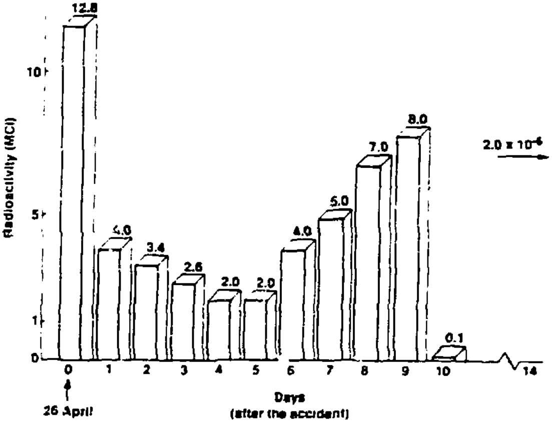

Fig. 9 Calculated daily release of radioactivity from the day of the accident until the quenching was successfully completed (Ahearne, 1987).

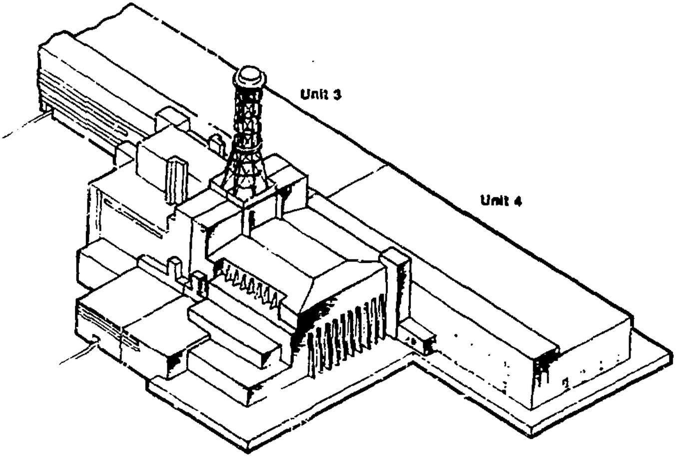

Fig. 10 Unit 4 burial (Snell and Howieson, 1986).

THE SITUATION TODAY

In March 1988, settlement in the completely new town of Slavutich (see Fig. 2) began. Slavutich, 45 km east of the plant site, is a replacement town for Pripyat. This will allow a return to normal shift work for the plant operators rather than the 15 day tour of duty where workers lived in an encampment at the village of Zelyony Mys, Fig. 2.

Pripyat is unlikely to be reinhabited on a permanent basis Many buildings have been taken over to conduct research on the effects of radiation, cleanup, and accident management techniques. The town of Chernobyl is also unlikely to be reinhabited. It was mainly used to house the decontamination workers and manage activities within the 30 km controlled zone.

Numerous modifications to prevent reactivity excursions have been made to all operating RBMK reactors as a result of the Chernobyl accident. These include limiting control rod motion, increasing scram speed, improved reactor instrumentation, and physical measures to make it difficult for operator to lock out safety systems. Improvements in management and supervision have occurred as has extensive operating personnel retraining.

LESSONS LEARNED

Some of the important lessons that have been re-emphasized during the Chernobyl accident are listed below.

- Reactor design problems and human errors led to the accident.
- Vigilance during critical operations.
    - Many operator or management mistakes occurred that led to the accident.
- Proper reactor design to assure negative void coefficients of reactivity.
- Proper design of shutdown and control systems including rapid and stable operation.
- Re-emphasize the necessity of containments to protect the environment.
- Importance of isolation mechanisms to protect one unit from an accident in another unit at multi-unit sites.
    - If the fire in the turbine hall had expanded, it could have affected the other units at the site and perhaps aggravated the situation.
- Geometric and structural layout of facilities and the importance of reducing the effects of accidents.
- Importance of effective fire fighting and being able to get men and equipment to the location of the fire (roofs) fast.
- The importance of management and operational personnel to understand and carry out safe operating procedures. The need for independent reviews of test procedures and modifications to established safe operating procedures.
- *Perhaps the most important lesson for structural engineers is to learn to design for failures - they will occur. Understand their consequences, protect against them where possible in layout of buildings and their design.*

REFERENCES

Ahearne, 1987, John F. Ahearne, Science, "Nuclear Power after Chernobyl," Vol. 236, May 8, 1987.

DOE, 1986, Report of the U.S. Department of Energy's Team Analyses of the Chernobyl-4 Atomic Energy Station Accident Sequence, DOE/NE-0076, Nov. 1986.

Edwards, 1987, Mike Edwards, National Geographic, "Chernobyl-One Year After," Vol. 171, No. 5, May 1987.

EPRI, 1987, EPRI Journal, "A Special Report: Chernobyl and Its Legacy," Vol. 12, No. 4, June 1987.

Kennedy, 1987, Richard T Kennedy, NEA Newsletter, "International Co-Operation Following Chernobyl," Vol. 5, No. 1, Spring 1987.

Kouts, 1986, Herbert Kouts, Brookhaven Lecture Series, "The Chernobyl Accident," BNL-52033, No. 227, September 24, 1986.

Malinauskas, et. al., 1987, A.P. Malinauskas, J.R. Buchanan, R.A. Lorenz, T. Yamashita, Mechanical Engineering, "Calamity at Chernobyl," February 1987.

Marshall, 1986, Eliot Marshall, Science, "The Lessons of Chernobyl," Vol. 233, Sept. 26, 1986.

Motor Columbus, 1986, Accident at the Chernobyl Plant-Description of the Plant, Review of Reported Events, Accident Scenarios and Initial Comparison with LWR Designs, Motor Columbus Consulting Engineers, Baden, Switzerland, June 1986.

NRC, 1987, U.S. Nuclear Regulatory Commission, Implications of the Accident at Chernobyl for Safety Regulation of Commercial Nuclear Power Plants in the United States, NUREG-1251, Aug. 1987.

Nuclear News, 1986, Nuclear News, "Chernobyl: The Soviet Report," Special Report, Sept. 11, 1986.

Rippon, 1988, Simon Rippon, Nuclear News, "Chernobyl Two Years Later," Vol. 31, No. 7, May 1988.

Snell and Howieson, 1986, V.G. Snell and J.Q. Howieson, Chernobyl-A Canadian Perspective, Atomic Energy of Canada Limited, CANDU Operations, Dec. 1986.

Wilson, 1987a, Richard Wilson, "Comments on the Accident at Chernobyl and Its Implications Following a Visit to the USSR on February 13-24, 1987," Harvard University, Cambridge, MA.

Wilson, 1987b, Richard Wilson, Science, "A Visit to Chernobyl," Vol. 236, June 26, 1987.