Canadian Nuclear Society Société Nucléaire Canadienne

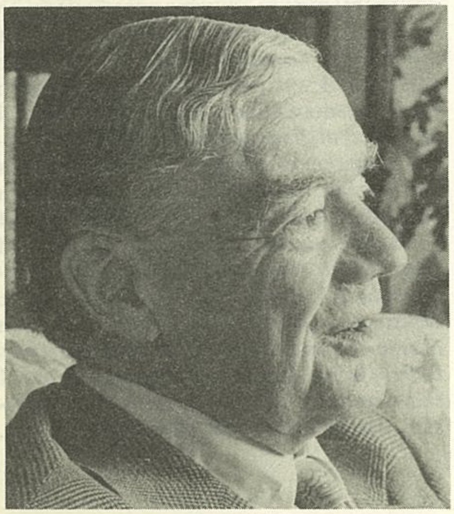
CNS BULLETIN SNC

Vol. 8, No. 2

March / April / mars / avril 1987

Perspective

Dr. W. Bennett Lewis – A Tribute



W. B. Lewis

"Who knows the individual hour in which
His habits were first sown, even as a seed;
Who that shall point as with a wand and say,
This portion of the river of my mind
Came from yon fountain?"

The Prelude, Part 2,
William Wordsworth.

" . . . the long burn-up with natural uranium, changing fuel under power, and zirconium for high temperature – seemed to burst out like a flower and pointed our thoughts into this new channel where they still prosper."

– Dr. W.B. Lewis, James Clayton Lecture delivered at the Institution in London, April 1959.

The early developments at the Chalk River Nuclear Laboratories, apart from their historical interest, provide an important link for us in understanding the processes which paved the path for subsequent evolution of the CANDU concept. The richness of the insights and the seminal nature of the early work is a remarkable example of creative science nurtured by foresight and courage. It also crystallizes, for later generations, the unique achievements of a talented and dedicated group of engineers and scientists. An appreciation by Mr. W.G. Morison and Mr. J.S. Foster describes aptly Dr. Lewis' leadership and the role as a catalyst amongst the pioneers.

In addition, we have selectively excerpted from the James Clayton lecture given by Dr. Lewis entitled "Some Highlights of Experience and Engineering of High-Power Heavy Water Moderated Nuclear Reactors." The excerpts are from the lecture published in *The Chartered Mechanical Engineer,* October, 1959. The excerpts focus on the essential aspects of the CANDU concept, the early lessons learned from fuel and cladding ruptures and the subtleties of reactor control.

An Appreciation by W.G. Morison

Dr. Lewis, affectionately known as the grandfather of the CANDU nuclear power system, died in the Deep River hospital on January 10, 1987. He was 78.

To those of us who had the privilege of knowing and working with Ben Lewis in the early years of the development of the CANDU reactor, his death brings back memories of exciting times and challenges when he led the Canadian scientific community to one of its most outstanding achievements. Dr. Lewis set very high standards for himself and his colleagues in tackling new and difficult ventures and in the innovation and vigor of his approach. A brilliant scientist in his own right, having worked with Lord Ernest Rutherford and Sir John Cockcroft at the Cavendish Laboratories in Cambridge, England in the 1930s, Dr. Lewis provided the spark that ignited the imagination in a diverse group of Canadian scientists and engineers to the superlative qualities of heavy water reactors. He championed heavy

Editorial

Good science writing is an important window to the public for us. Consequently, any changes on the science writing scene are noteworthy. It was, therefore, with considerable interest that the first issue of the new *Dimensions* magazine was awaited. *Dimensions* is the former *Science Dimension,* which was recently sold to a private sector company.

The premier issue of *Dimensions* contains the by now obligatory matched nuke pair: pro and anti. The pro article, entitled "Darlington: Energy of the Future," makes all the usual points about needing the energy, demonstrated safety, reduced dependency on fossil fuels, low environmental insult. However, it then drifts off curiously into unrelated areas. An offensive comment about 19th century Soviet drawing room methods is reproduced gratuitously from the *Daily Telegraph;* graphite reactors are tossed off as "antediluvian" in passing; a barb is directed at the British for their folly at "perhaps misguidedly opting for lightwater reactors".

The message of all this is not clear, unless it is that the world would be such a better place if only everyone would choose our reactors.

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Editorial

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Some kind words are then said about the CANDU system, including the competitive costs of the electricity that Darlington will produce. Embedded in this is a puzzling note to the effect that Darlington will not be susceptible to the effects of electromagnetic pulse because it contains fibre-optic communications equipment. Such assertions would indeed provoke further questions and debate that hardly seems fruitful. The recommendations of the Select Committee are noted as well.

The anti article is depressingly predictable. After dubbing Darlington "an $11 billion dinosaur," and coming out swinging at the Ontario Liberals, Ontario Hydro, and anyone else who gets in the way, the author launches himself into a Lovins-esque anti-nuclear sermon on energy. In case you are one of the industry diehards who still believe that nuclear power may yet become "too cheap to meter" (yes, he actually says it), you may be cheered to know that we don't need it. Probably we don't need the coal stations either. Only a few trivial matters prevent us from reaching this energy Nirvana. All we need to do is make Canada as energy efficient as Europe, and we'll be there; or we could simply rely on co-generation. You can also take heart from the fact that the world's oil reserves are stated to be at the same level as in 1974; or that the world's coal reserves have increased by 50%.

With the main message behind him, the author then returns to Darlington, predicting that in 2031, when it is retired, it will have the distinction of being the last nuclear plant to have been built on the continent.

There are a number of issues here, but the main one pertains to a question of editorial policy. The aims of *Dimensions*, as stated in the premier issue's editorial, are "to experience the reality of science and technology," "to satisfy your simple curiosity" and "to help you hold your own in an increasingly technological world." Can the staging of yet another head butting contest between utterly conflicting world views accomplish this? Does the information provided in either of these articles have the quality or depth to reflect the reality of science and technology in any way, satisfy anyone's simple curiosity, help anyone hold their own? Does it promote any kind of appreciation of the science or the technology involved? Is nuclear energy, as the pro-writer insists "absolutely essential" in our future, or as the anti-writer makes the case, totally undesirable and completely unnecessary, and can a worthy and cogent argument for both these points of view be developed on less than two pages of text?

The silence roars its displeasure.

Dr. W.B. Lewis

(continued from page 1)

water reactors at home and abroad, taking on any challenge with copious reports, papers and presentations on the importance of neutron economy and the economic potential of a variety of heavy water reactor concepts.

Dr. Lewis came to Chalk River in 1946 as Director of the Atomic Energy Research Division of the National Research Council of Canada, and when AECL was formed in 1952 became Vice-President, Research and Development. He was made Senior Vice-President (Science) in 1963, the position he held until his retirement from AECL in 1973. It was clearly a case of the right man at the right time. His inspiring and untiring leadership provided the confidence and courage needed for Canada to tackle the development of its own nuclear power system, a task that only one or two of the largest nations in the world have been able to master successfully.

Dr. Lewis also made a contribution to international co-operation and understanding of nuclear energy development as Canadian representative on the United Nations scientific advisory committee and as a member of the International Atomic Energy Agency advisory committee.

His outstanding scientific and technical achievements were recognized on many occasions by his Canadian and international peers. Dr. Lewis became the first Canadian recipient of the prestigious Enrico Fermi Award from the United States Department of Energy in 1982, for his exceptional and altogether outstanding scientific achievement in the development of nuclear energy. Dr. Lewis was co-winner of the Atoms for Peace award in 1967 for promoting international co-operation and was named Companion of the Order of Canada in 1968. He was a charter member and past president of the American Nuclear Society and an organizer of the United Nations' Geneva conference on atomic energy.

We have benefited greatly from his presence among us. Without Ben Lewis, it is doubtful that the Canadian nuclear program would be the outstanding success we enjoy today.

Dr. W.B. Lewis – An Appreciation by J.S. Foster

Dr. Lewis chaired a round table at the I.A.E.A. "Conference on Nuclear Power and the Fuel Cycle" held at Salzburg in 1977. In his opening remarks, he first referred to his Valubreeder, a CANDU reactor concept designed to extract 18MWd_t/kgU from 1.0% enriched uranium oxide and 36 MWd_t/kgTh from natural thorium oxide. He then went on to note:

- The days of low-cost energy still lie ahead.
- Nuclear energy will remain an abundant, low-cost and low-risk form of harnessed energy for thousands of centuries.
- From experience in Ontario, the cost of electricity from nuclear energy is expected to remain low (in constant dollars).
- The key to the above state of affairs is mutual confidence and co-operation.
- The people who see a problem in storing radioactive wastes safely are too ignorant to be trusted with the job.

Anyone who didn't know Dr. Lewis might be forgiven for thinking that these were simply extravagant statements designed to stimulate discussion. They were certainly intended to provoke reaction and Dr. Lewis was fully aware of their shock value, but they were not extravagant statements. They were expressions of strong convictions.

His knowledge of the abundance of the light and heavy elements and ways to exploit them, the success of CANDU which crowned his unrelenting pursuit of reactor efficiency, and the very satisfactory results of the experiments with vitrified fission products, begun 20 years before at Chalk River, combined to convince him of the potential abundance and cheapness of nuclear energy and of the safeness of producing it and of disposing of the wastes. He characteristically did not mince words in commenting on misguided notions.

My main association with Dr. Lewis was as one in charge of engineering cooperating with the leader of the research and development arm and the dominant scientist in the whole enterprise. I was continually impressed with the tremendous effort he made to understand all aspects of the undertaking and his phenomenal retention of information. Withal he was very human – sometimes critical, more often very considerate, and always appreciative of good work carefully thought out. He received ideas that he regarded as elegant, such as bi-directional fuelling, with what can only be described as glee. His father was an engineer in charge of a water works in England and it was evident he had a great deal of respect for him. I think some of this rubbed off on the profession. He liked to work with engineers and,

CNS BULLETIN SNC

ISSN 0714-7074

The CNS Bulletin is the membership newsletter of the Canadian Nuclear Society; 111 Elizabeth St., 11th Floor; Toronto, Ontario; Canada; M5G 1P7. (Telephone (416) 977-6152; Telex 06-23741). Published every two months; deadline for contributions 1st of every odd-numbered month.

Le Bulletin SNC est l'organe d'information de la Société Nucléaire Canadienne.

CNS provides Canadians interested in nuclear energy with a forum for technical discussion. For membership information, contact the CNS office, a member of the Council, or local branch executive. Membership fee is $40.00 annually, $20.00 to retirees, $5.00 to students.

La SNC procure aux Canadiens intéressés à l'énergie nucléaire un forum où ils peuvent participer à des discussions de nature technique. Pour tous renseignements concernant les inscriptions, veuillez bien entrer en contact avec le bureau de la SNC, les membres du Conseil ou les responsables locaux. La cotisation annuelle est de $40.00, $20.00 pour les retraités, et $5.00 pour les étudiants.

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provided their ideas were sensible, he had a high regard for their role.
On at least one occasion he used words from Clough's poem, "Say Not the Struggle Naught Availeth" to illustrate a point:

"And not by eastern windows only,
When daylight comes, comes in the light;
In front, the sun climbs slow, how slowly,
But westward, look, the land is bright."

It is almost a poetic paraphrase of what he said at Salzburg. The world can get too preoccupied with the apparent problems and sometimes painfully slow progress of the work at hand. Dr. Lewis worked very diligently on immediate problems but he never lost sight of the great promise that the gradual progress was heralding.

The James Clayton Lecture – Some Highlights of Experience and Engineering of High-Power Heavy-Water-Moderated Nuclear Reactors – by Dr. W.B. Lewis, C.B.E.

Excerpted from The Chartered Mechanical Engineer, October 1959. Presented April 10, 1959.

The years 1951 and 1953 produced landmarks in the engineering of heavy-water reactors. By July 1951 we had four years' experience of operating the NRX experimental reactor at Chalk River, and had completed the basic design of a 200-thermal-megawatt reactor, the NRU, to be a successor. The detailed design and construction of this large reactor had been commissioned at the beginning of the year 1951. In August in a report entitled 'An Atomic Power Proposal', I was able to note:

'It has proved possible in the NRX reactor to extract 110 million B.t.u. per lb. of uranium metal (>3,000 thermal megawatt days (MWD) per metric tonne) without any reprocessing. This means that at the present prices of uranium metal and coal or oil, uranium is three or four times cheaper as a fuel, even if no value at all is assigned to the plutonium or depleted uranium in the residual metal . . . . Moreover even after this long irradiation the metal retains more than 70 per cent of its reactivity. This is due to the plutonium produced. Means can therefore be foreseen of extending the irradiation still further with a further lowering of the mean fuel cost by a limited admixture of fuel elements enriched in one or more of the fissile nuclides U-235, U-233 or Pu-239.'

In 1951 it was a landmark, for no one else was even close to this achievement.

From the heavy-water reactor we now expect even cheaper fuelling because experiments indicate we shall obtain 10,000 MWD/tonne U from natural uranium in the form of uranium dioxide.

Quoting again:

'In the design of the NRU reactor means have been envisaged for running a physically small reactor continuously at high output. This makes it possible to envisage a simplified reactor with an output of 400 thermal megawatts from a charge of uranium less than 15 tons and likely to cost, perhaps, only $20,000,000 for the reactor itself. This could be coupled with steam-raising and electrical-generating plant, which at $100 per installed kilowatt capacity and assuming 26 per cent efficiency would add $10,400,000 for the 104,000 kilowatt capacity.'

These were not empty words. I had hoped that the report I was then writing might be released from secrecy, so I knew that I could not then say openly that we considered it practical to change the fuel in NRU rod by rod with the reactor operating at full power. This is now an accomplished procedure. The NRU reactor, I am happy to report, operates very satisfactorily in this respect.

Continuing with the quotations:

'It now appears practicable to operate a heavy-water system in the high levels of irradiation involved, at 550°F (288°C) and 1500 lb/in^2, using a stainless-steel-lined pressure vessel and, if it is not possible to get aluminum to stand up to this temperature in a water system, it seems that zirconium can be used for sheathing the uranium and for other internal minor structures.'

Again the words were guarded. It is now well known that we had in fact operated zirconium-clad fuel in stainless-steel pressure tubes in water at the temperature and pressure quoted. Zirconium was new for such uses at that time, but now we have used it for the pressure tube as well.

These three points I have quoted – the long burn-up with natural uranium, changing fuel under power, and zirconium for high temperature – seemed to burst out like a flower and pointed our thoughts into this new channel where they still prosper.

By contrast, in 1953 we learnt by suffering. It was in December 1952 that the NRX reactor had its power-surge accident, melting some of the uranium fuel and leaving 10,000 curies of mixed fission products seeping into the concrete walls from the flood water in the basement. Much more activity was lying in an uncertain state in the reactor vessel.

Amongst the points we learnt there were four important lessons:

- To have a very healthy respect for the radioactivity of fission products.
- That the NRX reactor could be restored. It was in fact increased from 30 to 40 MW power rating in the process.
- That there are subtleties in the reliable control of reactors.
- That we were not troubled by radio-iodine.

The flood water took care of both the strontium and iodine that in other circumstances present the major hazards.

Our period of suffering had two phases. At first we were preoccupied with our problem of discovering the extent of the damage to the reactor and means for its restoration. Later in the year 1953 we had to be patient while the reconstruction was in progress. This gave us time for some meditation that has since borne fruit. Our meditations concerned safety and economy, the twin criteria of good engineering.

Fuel and Cladding Ruptures

We have deliberately gained a lot of experience on defected or ruptured fuel. We have also encountered unexpected fuel failures that extend the repertoire. For use in high-temperature (525°F) water, UO_2 clad in zirconium alloy is highly promising. The UO_2, after irradiation, if not before, is a sintered compact liable to crack. It is not bonded to the cladding, so when a hole or crack penetrates the Zircaloy, fission product gases from the interior are released to the water. Their radioactivity appearing in the water signals the rupture. It is very rare for a serious situation to develop rapidly so the reactor is not shut down and irradiations have been continued for many months.

When contemplating the operation of a large power reactor, however, we envisage that as soon as convenient any ruptured fuel element would be removed. To identify the failed element the water from each channel in the reactor would be sampled. The water coolant recirculates so rapidly that following a rupture the level of radioactivity rises in all the channels. We have found that a sudden change in operating power level usually releases a burst of fission products and this promises a valuable technique for locating the faulty element. Having shut a reactor down, it has proved often very difficult to locate even a rod with a severe rupture.

The many small advantages to be gained from changing fuel at power cumulatively make it almost essential for economic power. First and most important is the small margin of excess reactivity wasted after a fuel change. Secondly, the ability to remove faulty fuel without loss of operating time reduces the integrity required of fuel cladding to a simple economic assessment of fuel supply cost.

This license in fuel integrity must not, however, be interpreted loosely. Very serious ruptures are possible with badly designed fuel. For example, if a large void space is left inside the fuel cladding, and if a small hole penetrates the cladding, the void is liable to fill with water when the reactor is shut down. On start-up this water may develop a very high pressure within the fuel and explode it. We do not consider it safe to use flat fuel elements of UO_2 except in very small sizes for a similar reason. Even though no internal void is initially present, a small excess internal pressure will distend the sheath. We encountered serious trouble in the NRU reactor in this way from the use of unbonded flat sheathing over uranium metal. The pressure drop along the coolant channel was enough to distend the sheath when punctured at the high-pressure end.

These waterlogging effects in UO_2 offer, therefore, an advantage if kept to small voids, because they serve to identify a failed fuel element, but threaten disaster if the void is too large. Properly designed UO_2 fuel promises to be very safe and preferable to any other economical uranium fuel yet known.

Reactor Control

We envisage heavy-water power reactors controlled entirely by the level of the cool heavy-water moderator. Following the NRX accident we planned to change this to eliminate the fine control rods and to share the shut-down action between a smaller number of shut-down rods and the dumping of the moderator.

The system promises some advantages for the power reactors both in safety and economy. I will mention just two points, both of which are merits of the gas balance system of suspension planned for NPD-2 and CANDU. Any freely falling shut-down rod to be effective must control a significant reactivity, say, 5 mk each, if there are 15 of them. A bursting pressure tube can produce a disruption of the thin calandria tube and either interfere with the free fall of a shut-down rod or even knock one aside that is down. This has to be ensured against by multiplicity of the rods and provision of an excess number. This raises initial and maintenance costs. In contrast, when no shut-down rods are provided and the moderator is suspended by balance of gas pressure, any rupture into the heavy-water moderator will upset the gas balance in such a way that the moderator is rapidly dumped out. It can be arranged that this rate of dumping is much greater than any inflow from the coolant. The second point utilizes a system of control valves. There are three independently operated trip circuits in parallel. Each controls two of the six valves. Any two trip lines would open two valves in series in the same line. This allows gas to flow to equalize the pressure over the two heavy-water surfaces and thus cause the heavy water to be dumped. This system has the essential property that any one trip line may be deactivated and tested without disturbing the protective action of the system. The deactivation of individual trip lines may be applied as a routine test, with the reactor in full operation and the actual motion of the valves may be observed. If this action is recorded in the log, then study of the log reveals whether this routine check is being made frequently enough to be sure that the chance is negligible that two trip lines would simultaneously fail in such a way that the necessary number of valves is not opened. The system is also very resistant to major disasters. Suppose, for example, all the valves get frozen shut. Provided this is discovered, no harm need result. Merely stopping the helium blower will still dump out the heavy water.

To give a further example of subtleties of reactor safety systems, we have a general rule that any changes to the control system should, if possible, be made with the reactor at power. For example, suppose a resistor is to be changed in an electronic instrument that is part of the control system. Suppose, further, that by some error the mechanic misinterprets his instructions and changes the wrong component. In operation there are three instruments constantly intercompared and any discrepancy is brought to the attention of the operator. With the reactor shut down, the mistake might pass unnoticed, and worse still, the mechanic might have repeated his error in all three instruments, so that the fault might be undiscovered until too late.

I hope I have said enough to indicate that what may seem obvious cannot be allowed to pass unchallenged and the intuitive reactions of engineers and operators are not always to be trusted.

Conclusion

Looking back, our rate of progress since 1951 seems slow and this must be attributed to the circumstance of abundant power in which we live. It is only looking forward that we see the complete utilization of water power resources in important industrial areas. Costs of power will still be low, and this sets us a challenging target. Now the scientific and technical problems have been reduced to manageable proportions and brought into the realm of engineering and estimates. Others may be able to take advantage of our development, and we hope we shall not find ourselves standing alone much longer in this low cost competition.

W.B. Lewis

"With them the seed of Wisdom did I sow,
And with mine own hand did wrought to make it grow;
And this was all the harvest that I reaped – "

Edward Fitzgerald

Perspective Compiled by Jatin Nathwani

FYI

Former AECL President Lorne Gray Dies (Staff)

Lorne Gray, President of Atomic Energy of Canada Ltd. from 1958 to 1974, died March 2 at his home in Deep River, Ontario on his 74th birthday.

Gray was born in Brandon, Manitoba and earned his Master of Science degree in mechanical engineering at the University of Saskatchewan.

During W.W. II he reached the rank of Wing Commander with the Royal Canadian Air Force. In 1949 he became Chief of Administration, National Research Council Chalk River project, and with the formation of AECL in 1952, he became General Manager of the Chalk River Nuclear Laboratories. Two years later he became Vice President, Administration and Operations.

While President of AECL, controversy arose over the AECL use of agents and fees to win the CANDU reactor contracts with South Korea and Argentina. However, Gray will be remembered as the driving force behind the successful CANDU export drive.

Gray was named a Companion of the Order of Canada in 1969 and in 1973 was awarded the gold medal of the Association of Professional Engineers of Ontario.

Sizewell Report Published (Staff)

Sir Frank Layfield's report on his 4-year Sizewell B public inquiry was published January 26, and finds that the expected economic benefits to the UK from a PWR to be built at Sizewell are sufficient to justify the risks in its construction and operation. The 3000 page report agreed with the Central Electricity Generating Board that pressurized water reactors would be safe, efficient and necessary to serve future electrical demand, although it found that the cost-saving case was not as strong as made by the CEGB. The report was also finished before the Chernobyl accident and the fall in coal prices. The Thatcher government has just given its go-ahead to the project which could be the first of as many as six PWRs, but faces an election any time until spring 1988. The opposition Labour Party has pledged to cancel construction of a Sizewell PWR if it comes into power.

Nuclear Liability Act Challenged (Energy Probe)

The Toronto-based environmental group Energy Probe announced March 3 a constitutional challenge to the Canadian Nuclear Liability Act, the federal law that limits nuclear reactor operators' liability to $75 million. Representing Energy Probe in this case is a team of seven lawyers headed by Clayton Ruby.

Ontario Nuclear Safety Review Seeks Input (ONSR)

In response to a recommendation of the Select Committee on Energy, the Minister of Energy of Ontario established the independent Nuclear Safety Review, Dr. F. Kenneth Hare of the University of Toronto, Commissioner. The review is examining:

- The safety of the design of Ontario Hydro's CANDU nuclear generating plants.
- The safety of the operation of the above.
- The associated emergency plans.

The report of this review is due early in 1988. The Ontario Nuclear Safety Review announced March 26 it is willing to receive the written views of any interested individual or organization with respect to the above specific terms of reference and will accept briefs up to and including September 1, 1987. In suitable cases, financial assistance may be provided for the preparation of submissions. Those who wish to apply for funding are invited to submit written proposals by April 15, 1987. These proposals should be one or two pages in length, and include an outline of the submission, a preliminary biography, a description of the experience of the individual or group in the nuclear safety field, and short résumés of the principal researchers. Contact: Peter M. Fraser, Staff Scientist; Ontario Nuclear Safety Review; Suite 303, 180 Bloor Street West; Toronto, Ontario; M5S 2V6. Tel. (416) 923-5791.

The Canadian Nuclear Society will be making a submission.

TECHNICAL SUPPLEMENT

CNS Bulletin Mar./Apr. 1987 Canadian Nuclear Society

THE CHERNOBYL ACCIDENT: A REVIEW AND ASSESSMENT OF REACTOR DYNAMICS ASPECTS OF THE EVENT

John C. Luxat

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Abstract – *On April 26, 1986 a reactivity initiated accident occurred in Unit 4 of the Chernobyl nuclear generating station. The resulting super-prompt critical power excursion resulted in the explosive destruction of the reactor and associated structures. A review of the events leading to the accident, and the accident itself, are presented with an emphasis on the reactor dynamics aspects of the event.*

INTRODUCTION

On April 26, 1986 a reactivity initiated accident occurred in the fourth unit of the Chernobyl nuclear generating station. This unit, the most recent of the four operating RBMK-1000 reactors at the site, located approximately 100 km north of the city of Kiev in the Ukraine, was destroyed in the course of the accident. The explosive destruction of the reactor and the reactor building structures led to a large release of radioactivity to the environment, which when detected in Sweden provided the first indications outside the Soviet Union of the accident.

A detailed account of the accident and its consequences was presented by a Soviet delegation to the International Atomic Energy Agency (IAEA) sponsored post-accident review meeting held in Vienna during the last week of August 1986. A great deal of information concerning the accident was documented in a report prepared by the USSR State Committee on the Utilization of Atomic Energy and released at this meeting [1]. In addition, the International Nuclear Safety Advisory Group (INSAG) to IAEA produced its own report on the meeting [2].

As presented by the Soviets the accident was, in simple terms, a reactor runaway in which positive reactivity was inserted at a rate that exceeded the rate at which compensating negative reactivity could be inserted from the reactor control and shutdown systems. The resultant power excursion led to a rapid release of energy in the core and its explosive destruction.

However, as in most past accidents, a series of preceding events occurred which directly contributed to the terminal event. Subsequent to the IAEA post-accident review meeting, the events at Chernobyl Unit 4 have been assessed with the aid of computer simulations to gain additional insight into the specific dynamics of this accident. It should be noted, however, that this accident did not present any previously unknown phenomena, as was stated in the conclusions of the INSAG report.[2].

The event sequence and the power excursion are discussed below with an emphasis placed on assessing the reactor dynamics of the event.

The Planned Test

A test of a safety-support function had been planned when taking Unit 4 down for annual maintenance. The test was to determine how long a turbine-generator, when disconnected from its steam supply, could continue to supply electrical power to a feed pump that drives the third channel of the short term, high pressure Emergency Core Cooling System (ECCS). The other two channels employ passive accumulators. Previous tests had demonstrated that the generator voltage drops too rapidly as the turbine runs down on its mechanical inertia. Modifications to the generator exciter controls had been made and were to be tested at this outage. Since emergency injection during the test was to be avoided, the electrical load of the ECCS feed pump was simulated by operating the fourth main coolant circulation pump. To keep the loops balanced neutronically, and to assure forced circulation after the turbine generator was tripped, all four pumps were operating in both loops (see Figures 1 and 2).

The Precursor Event Series

At 1:00 hours on April 25, a slow power reduction to 50 per cent was initiated on Unit 4. Twelve hours later, at 13:05 hours, with the unit at 50 per cent, one of the two turbine/generators (T/G No. 7) was disconnected from the steam supply and the unit electrical load was divided between the operating T/G, No. 8 and the station electrical service. At 14:00 hours, the emergency core cooling system (ECCS) was valved out from the main coolant loop according to test procedure. However, because of grid demands, Unit 4 continued to operate at 50 per cent full power for another ten hours until 23:10 on April 25th. ECCS remained impaired during this period.

As shown in Figure 3, the xenon poisoning transiently increased during the period of operation at 50 per cent full power, necessitating the removal of an estimated 73 control rods. This estimation is based on simulation of the xenon transient associated with the power history shown in Figure 3, the details of the RBMK-1000 reactor control systems provided by the Soviets [1], and estimates of the reactivity feedback effects associated with changes in power level.

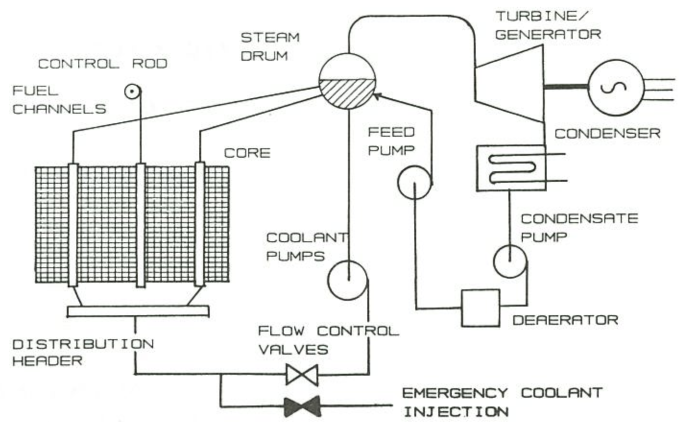


Figure 1:
Schematic Diagram of the RBMK-1000

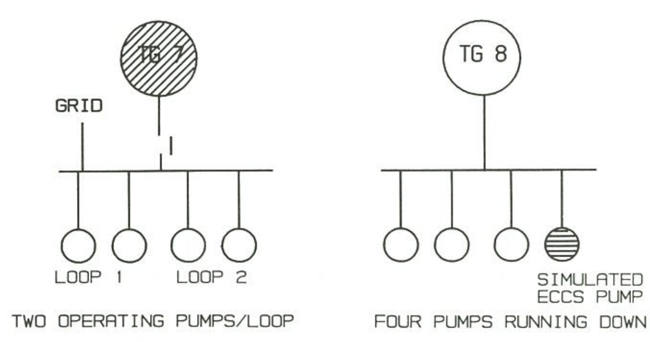


Figure 2:
Test Configuration to Simulate TG 8 Electrical Load With 3 Main Coolant Pumps and ECCS Feed Pump

When the power reduction was resumed at 23:10 hours, the intent was to hold power in the region of 700 to 1000 MW (approximately 20 to 30 per cent of full power). However, at this power level the local automatic control (LAC) system – spatial control system – was turned off. This appears to be an inappropriate action since the lower order harmonic flux modes of the RBMK-1000 reactors are xenon unstable at this power level. The Soviet documentation quotes 10 per cent as being the power level at which LAC is turned off, which is consistent with the low power level for stabilization of the first azimuthal mode; the least subcritical reactor harmonic mode. More importantly, the operator had failed to adjust the setpoint of the low power automatic power regulation system to the desired power level (the setpoint was probably set at a default low power level of approximately 1 per cent to accomodate a normal full shutdown). As a result, reactor power rapidly dropped to 30 MW (0.94 per cent full power). The resultant net negative reactivity due to void collapse and graphite cooldown, together with the second xenon poison transient, required the additional removal of a substantial number of control rods over a short period of time, as shown in Figure 3.

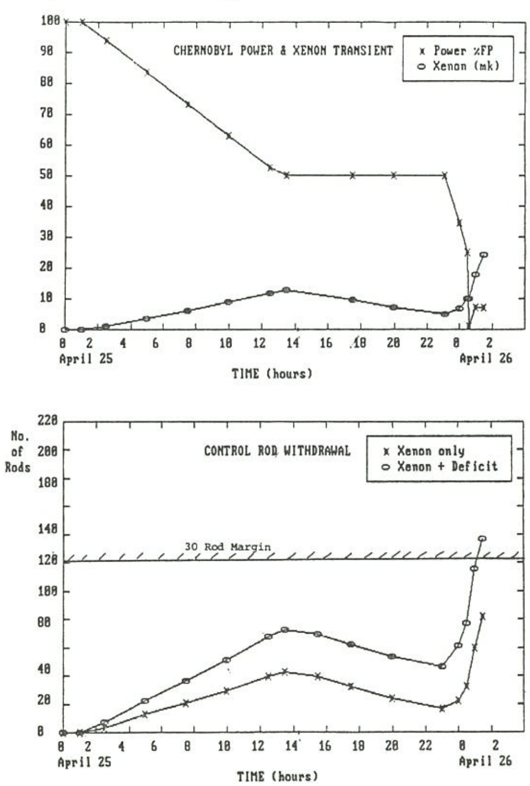


Figure 3:
Estimated Xenon Transient and Control Rod Withdrawal History Based on Stated Power Reduction Transient

Xenon poisoning was continuing at 1:00 hours on April 26 when the operators managed to bring the reactor power back to approximately 200 MW. In so doing, essentially all control rods, apart from the rods in the three Automatic Control (AC) groups for bulk power automatic regulation, were withdrawn. Note that there are 4 rods in each of the three AC groups. The removal of this number of rods was in direct violation of an operating procedure which required that a minimum of 30 effective rods be inserted to provide reactivity margin, and an operating principle that demands an immediate reactor shutdown if the reactivity margin drops below 15 rods effective. These operating procedures and principles are designed to assure that the constant void reactivity feedback coefficient is maintained at an acceptable level. The drop in reactor power when LAC was turned off was perhaps the key initiating event since it completely disrupted the planned procedures and put pressure on the operators to stabilize the reactor before xenon poison-out occurred.

At approximately 1:00 hours on April 26, the decision to proceed with the test was taken. The fourth main circulation pump in the two loops were started at 1:03 and 1:07 respectively. However, this led to excessively high circuit flow due to the reduction of the hydraulic resistance that accompanied the collapse of core void. Furthermore, this was also accompanied by a drop in steam drum separator pressure and an induced drum level transient. In order to prevent trips on low drum pressure and low drum level, these trips were blocked and manual adjustments made to stabilize these parameters. One measure taken was to rapidly increase the feedwater flow at 1:19 hrs by a factor of four times the required flow. The increased feedwater flow increased the subcooling of the water leaving the steam drums (the feedwater enters at the bottom of the drum where it mixes with the saturated water in the drum). After a transport delay of approximately 30–40 seconds (dependent on main circulation flow), the more subcooled water reached the inlet to the core, further reducing the void in the core, adding negative reactivity and forcing the manual withdrawal of additional control rods.

This reduction in steam generation initiated another transient dip in the steam drum pressure and the operators closed the condenser bypass steam bleed valve to limit the dip in pressure. At 1:21:50, with the steam drum level having increased substantially, the operators then reduced feedwater flow to below the balance rate corresponding to the 200 MW power level (a value of 67 per cent of the balance flow rate was quoted). Some twenty seconds later, at 1:22:10, the effect of reduced subcooling at the core inlet, initially due to the dip in pressure, led to an increase in core voiding and two groups of automatic regulating rods started to drive in to compensate the positive reactivity. Despite this ongoing transient, the test was initiated at 1:23:04 by closing the stop valve to turbine-generator No. 8. Note that just prior to initiating the test, the operators had determined a reactivity margin of only 6–8 rods in the core. Also, prior to initiating the test, an AZ–5 trip (emergency shutdown) that is initiated on closure of both turbine-generator valves had been inhibited. This was not part of the test procedure. The inhibiting of multiple reactor trips would appear to be dictated by the desire of the operators to initiate another test in the event that the first was not successful.

Given the increasing xenon poisoning, the operators were, in all likelihood, pressured to complete the test as soon as possible before the reactor poisoned out.

The Accident Sequence

The closure of the turbine stop valve initiated a slow recovery in the steam drum pressure which, in turn, slightly reduced core voiding. The control rods changed direction and, for a short period, started to drive out. However, a "slug" of low subcooled water from the steam drum, created by the large reduction in feedwater flow, initiated a rapid increase in core inlet voiding which progressed up the channels. The voiding rate was further enhanced by the reduction in main loop circulation flow due to the reduction in speed of the pumps that were being powered from the "running down" turbine-generator No. 8. Additional enhancement of the void reactivity feedback will have occurred from the large bottom-to-top axial flux tilt that developed rapidly as a combination of a) the pre-existing flux distribution that was tilted from bottom-to-top due to excess xenon buildup at the top of the core, b) the void distribution that was biased toward the bottom of the channel, and c) the automatic control rods that were driving into the core from the top.

Up to 1:23:40 the automatic power regulator had not been able to compensate for the void reactivity insertion and the power had doubled – at lower powers the delayed super-critical power increase, while large in relative terms, is deceptively small in absolute terms. For whatever reason – power increasing, rods driving in, or possibly the indication of positive reactivity on the reactimeter – an AZ–5 emergency shutdown was manually initiated at 1:23:40. Three seconds later, at 1:23:43, the trips on high power and low period (high lograte) initiated. However, with about 25 mk of differential void reactivity available at that time and with the increased voiding rate, the reactor became super-prompt critical before the rods had time to drive into the core. The Soviet analysis indicates an initial power pulse of approximately 140 times full power, that was limited by fuel Doppler reactivity feedback (worth approximate 12 mk per 1000°C fuel temperature rise). At some point, a significant number of channels ruptured in the lower part of the core. Coolant discharged into the reactor space surrounding the graphite, pressurized it, lifting the top plate above the reactor, and shearing all the outlet feeder connections to the channels. In addition, the Soviet analysis then predicted a subsequent power pulse of approximately 480 times full power due to rapid vaporization of coolant. The resultant fuel fragmentation and dispersal into the reactor well of the lower part of the core (graphite and fuel) provide the ultimate shutdown mechanism. The control rods would have been totally disabled from entering the core by the lifting of the upper plate. The Soviets reported that two explosions were heard around this time, separated in time by 2 or 3 seconds.

Further discussion of the reactor power excursion is given in the following section.

Analysis of the Power Excursion

An analysis of the void reactivity insertion that initiated the Chernobyl power excursion has been performed. The purpose of this analysis is not to duplicate the Soviet calculations, but to get a quantitative feel for the reactivity insertion rates associated with the three main factors involved, namely (1) the decrease in inlet subcooling to the core, (2) the decrease in main circulation flow, and (3) increase in power-to-coolant.

Inlet Coolant Subcooling Transient

A reduction in feedwater flow from 225 kg/s to approximately 37.5 kg/s occurred over a 40 second interval, starting at 1:21:50 and ending at 1:22:30. The feedwater flow rate directly controls the temperature of the inlet coolant according to the flow-mixing temperature given by:

$$T_{SDX} = A\ T_{SAT} + (1-A)\ T_F \qquad (1)$$

where
T_{SDX} = cooling temperature exiting steam drum downcomers
T_{SAT} = saturation temperature in steam drum
T_F = feedwater temperature
$A = \frac{W_C}{(W_F + W_C)}$
W_C = coolant flow in loop
W_F = feedwater flow to steam drums in a loop

The core inlet temperature is given by:

$$T_{IN} = T_{SDX} + B\ \Delta hp$$

$$\Delta hp = \text{pump enthalpy rise}$$

$$= \frac{(\text{Pump Theoretical Power}) \times (\text{Number of Operating Pumps in Loop})}{(\text{Pump Efficiency}) \times (\text{Coolant Flow in Loop})}$$

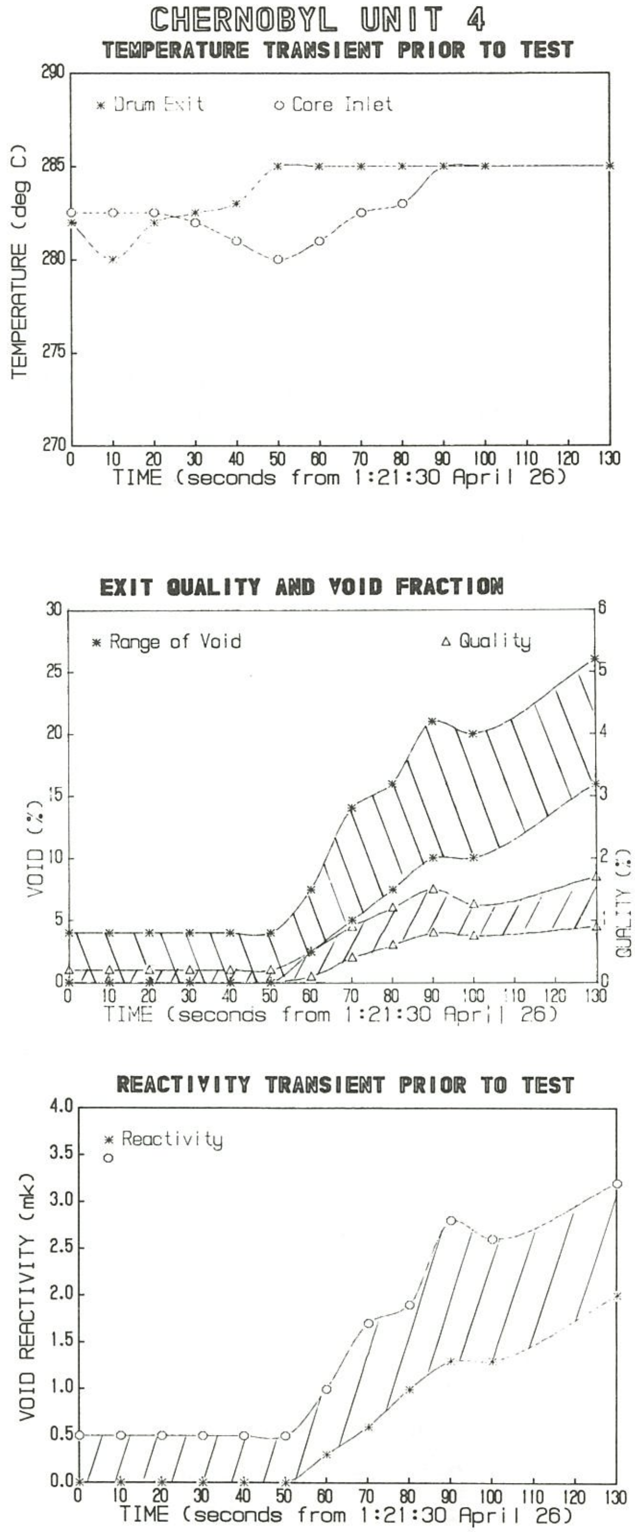
The coolant inlet temperature computed from the above equations for nominal full power operation, and for the conditions prevailing at 1:21:50 and 1:22:30 are shown in Table 1. As can be seen from this table, the coolant travelling to the steam drum was marginally subcooled at the nominal operating pressure of 7 MPa. With the transient reduction in steam drum pressure there was essentially no subcooling. The estimated core inlet temperature, core exit quality and exit void fraction transients are shown in Figure 4 as a function of time from 1:21:30, shortly before the feedwater flow reduction began. By 1:23:30 the transient subcooling reduction had inserted between 2.0 mk and 3.4 mk of void reactivity, as shown in Figure 4. The range of variation in the reactivity estimates shown in this figure reflects the uncertainty associated with the actual pressure during this interval.

TABLE I

Chernobyl Inlet Coolant Temperature Variations

Loop Thermal Parameters (for each of the two loops)		
Main coolant flow (normal)	= 5222 kg/s (three pumps)	
Main coolant flow (April 26)	= 5906 kg/s (four pumps)	
Full power feedwater flow	= 805.5 kg/s	
Drum separator water temperature	= 284°C	
Feedwater temperature	= 168°C	
Main Coolant Pump theoretical power	= 3354 kW	
Coolant Pump efficiency (nominal)	= 78% (from Soviet Report, Ref 1)	
Coolant Enthalpy rise across pump	= 2.5 kJ/kg	
Nominal Full Power Conditions		
Coolant flow	= 5222 kg/s.	
Feedwater flow	= 805.5	
Calculated T_{SDX} (equation 1)	= 268.5°C	
T_{in} (equation 2)	= 269.5°C	
Saturation pressure at T_{in}	= 5.5 MPa	
1:21:50 April 26 (High Feedwater Flow)		
Coolant flow	= 5907 kg/s.	
Feedwater flow	= 225 kg/s	
Calculated T_{SDX}	= 279.8°C	
T_{in}	= 281.1°C	
Saturation pressure at T_{in}	= 6.54 MPa	
1:22:30 April 26 (Feedwater Reduced)		
Coolant flow	= 5907 kg/s.	
Feedwater flow	= 37.5 kg/s	
Calculated T_{SDX}	= 283.3°C	
T_{in}	= 284.6°C	
Saturation pressure at T_{in}	= 6.9 MPa	(above core pressure at this time)

Figure 4:



Flow Reduction and Power Increase: Reactivity Insertion

The rate of change of coolant enthalpy rise above saturation can be expressed as:

$$\frac{d\Delta h}{dt} = \frac{Q_{100}}{W_{100}} \bullet \frac{d}{dt}\left(\frac{Q}{W}\right) - \frac{d}{dt} h_{in} \qquad (3)$$

where
Q_{100} = 100 per cent thermal power (kW)
W_{100} = Coolant flow prior to reduction (kg/s)
Q = relative thermal power level (pu)
W = relative coolant flow (pu)
h_{in} = inlet coolant enthalpy

Following trip of turbine generator No. 8, the relative flow run-down can be approximated by:

$$W = 1 - Ct \qquad (4)$$

where
C = coefficient of rundown
t = time from start of flow rundown

Considering the rate of enthalpy change due to power and flow alone, yields:

$$\frac{d\Delta h}{dt} = \Delta h_{100}\left(\frac{1}{(1-Ct)}\frac{dQ}{dt} + \frac{C}{(1-Ct)^2} Q\right) \qquad (5)$$

Now the change in coolant flow quality is given by:

$$\Delta X = \frac{\Delta h}{h_{fg}} \qquad (6)$$

and change in void fraction by:

$$\Delta \alpha = \frac{\delta \alpha}{\delta X} \bullet \Delta X = K_1 \Delta X \qquad (7)$$

Based upon the conditions prevailing at 1:23:04, the reactivity insertion rate can be expressed as the sum of a rate of power change component and a rate of coolant flow reduction component using (5) through (7) and the relationship:

$$\Delta \rho = K_v \Delta \alpha$$

where K_v = void reactivity coefficient (30 mk/unit void)

This gives the following values:

Power Change

$$\frac{d\rho}{dt} = K_v K_1 \bullet \frac{\Delta h_{100}}{hfg} \bullet \frac{1}{(1-Ct)} \frac{dQ}{dt}$$

$$= 79 \frac{dQ}{dt} \text{ mk/s} \quad (\text{at } t = 0)$$

Flow Reduction

$$\frac{d\rho}{dt} = K_v K_1 \bullet \frac{\Delta h_{100}}{hfg} \frac{Q}{(1-Ct)^2} \bullet C$$

$$\simeq 0.028 \text{ mk/s} \quad (\text{at } 7\%) \text{ FP}$$

As can be seen from the above, for conditions existing at the time of the test, the reactivity insertion rate due to coolant flow rundown is approximately equal to the power increase component for rates of increase in power to coolant given by:

$$\frac{dQ}{dt} = \frac{0.028}{79} \times 100 \quad \text{per cent FP/s}$$

$$\simeq 0.035 \text{ per cent FP/s}$$

Obviously, once the power to coolant starts to increase, the reactivity insertion rate rapidly becomes dominated by the positive feedback effect of the power-to-coolant.

More interestingly, the rate of increase in power-to-coolant required to exceed the 1-Beta/second reactivity insertion criterion quoted by the Soviets is in the modest range:

$$\frac{dQ}{dt} = 6.3 \text{ to } 12 \quad \text{per cent FP/second}$$

This variation accommodates the variation in the slope of the void fraction/quality curve, K_1, over the range of coolant quality relevant to the initial part of the power excursion. Transient analysis was performed in which the flow rundown and power rate dependent reactivity insertion rates were modelled, and the variation in the void fraction slope multiplier, K_1, with increasing quality was accounted for. The resultant reactivity and neutron power transients essentially confirm the Soviet analysis as shown in Figure 5 and 6. Furthermore, because of the additional shift in the power distribution to the bottom of the core when a) the inlet subcooling reduction occurred, and b) the regulating control rods (two groups) were inserted into the upper part of the core, the local reactivity feedback will have been strongly dominated by the power feedback due to void in the bottom part of the core.

The transient excitation of the 1st axial mode by the void reactivity insertion will have increased the power in the bottom half of the reactor by at least a factor of 1.5 above the average neutron power. This is shown in Figure 6. Note that because of the strong bottom-to-top tilting, the insertion of control rods from the top would not have introduced much reactivity until they reached the centre of the core (approximately 8.5 seconds after the AZ–5 trip button was pressed). However, by this time the reactor core had already been destroyed.

Energy Deposition in the Fuel

Based upon the neutronic transient analysis, the net energy deposition in the fuel during the first power pulse (limited by Doppler feedback) was at least 30-36 full-power-seconds. Note that the net energy deposition is defined as the integrated difference between power generated in the fuel and power transferred from the fuel to coolant. This range takes into account the uncertainties in net energy deposition related to time to fuel sheath dryout. The energy deposition transient in the maximum rated fuel element (35 kW / m) and average rated element (~29 kW / m) in the bottom of the core is shown in Figure 7 in units of cal / g. As can be seen, the initial pulse deposited in excess of 300 cal / g in a maximum rated element. Certainly at these energy depositions there would be a significant amount of very hot damaged fuel in the bottom part of the core and a significant number of pressure tubes could have failed due to the first power pulse. The force reversal on the fuel following rupture of pressure tubes at the bottom of the core, together with the subsequent rapid coolant voiding and the resultant second, larger power pulse, will have forced fragmented, dispersed hot fuel downward into water-filled inlet feeder pipes. This could have resulted in a steam explosion. Alternatively, the high mechanical energy conversion associated with the larger second energy deposition could have led to an explosive fuel fragmentation process with the fuel dispersing downward and outward in the reactor well.

Figure 5:

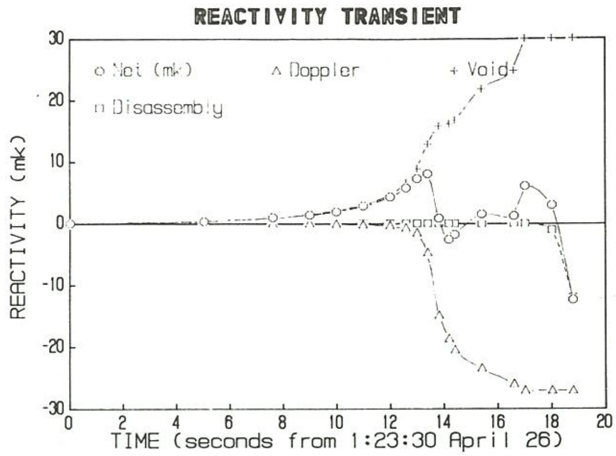


Figure 6:

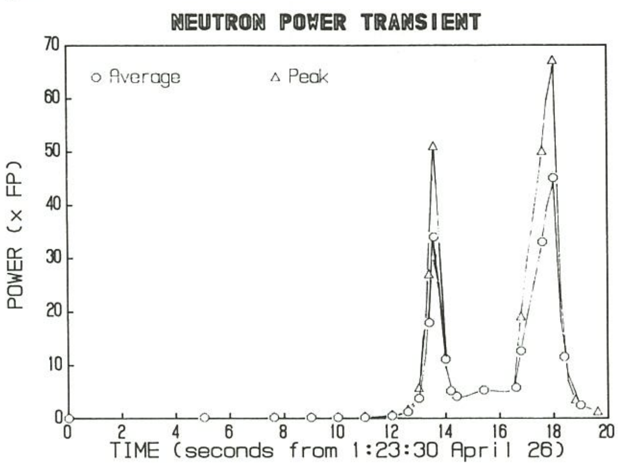
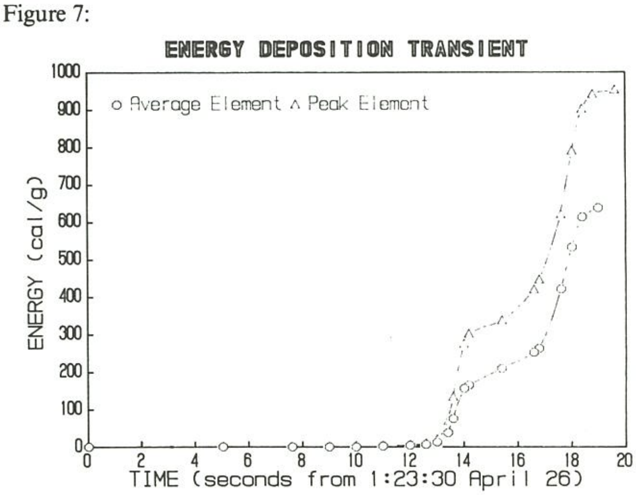


Figure 7:



Core Damage

The Soviets estimated that the largest energy depositions occurred in the bottom part of the reactor and that major fuel relocation occurred from the bottom 30 per cent of the core. They also estimated that between 4 and 6 per cent of the fuel was ejected outside the reactor building. Subsequent gamma scan measurements, performed by getting access to the bottom of some of the control rod channels, indicated that fuel was located primarily in the reactor well – in the core, in the lower feeder tubes and connecting piping and some other indeterminate places in the lower part of the reactor well.

These observations are consistent with the initial failure being channel ruptures at the bottom of the core. The resultant forces exerted on the fuel in the channels would be initially downward and radially outward, as dictated by the ruptures. The coolant discharge into the reactor space would rapidly pressurize the small free volume, rupturing it then overpressurizing the upper slab – the Soviets quoted two atmospheres (200 kPa) as the overpressure required to lift the structure above the core.

Visual observations indicated that the upper structure had been lifted and "hinged" open on the north side – somewhat like the lid of an opened can. The steam drum separator on the north side was displaced and still showed the feeder tubes connecting to it.

The entire north wall, as well as the structure directly above the reactor well, was demolished. A video tape shown at the Vienna meeting demonstrated very graphically the extreme devastation of the outer structures on the north side, including the confinement areas enclosing the steam separator and the main circulation pumps.

Post-Accident Stabilization

The initial fire fighting after the accident was related to containing multiple fires started by hot molten debris landing on roofs of adjoining structures and within the turbine hall. The material dumped on the reactor itself was as follows:

- Boron-carbide, added to assure guaranteed shutdown and as a preventative against any possible recriticality.
- 800 tonnes of Dolomite – a heat absorbent material intended to assist in smothering graphite combustion by using up available oxygen to form carbon dioxide.
- 2400 tonnes of lead – to provide gamma shielding and to absorb heat.
- Sand and clay to form an upper packed bed filter.

An estimated 10 per cent of the graphite in the reactor burned. Soviets also indicate that their understanding of the aerosol releases was that they were driven by low temperature oxidation of UO_2.

SUMMARY

The accident at Chernobyl Power Station Unit 4 was a reactivity initiated accident during which the reactor became super-prompt critical. The energy deposition associated with the large, extremely rapidly developing power pulse resulted in failure of the fuel channels, and fragmentation and dispersal of the lower part of the reactor core. The analysis of the reactor dynamics presented in this paper provides a quantified understanding of the reactor power driven reactivity feedback that dominated the late stages of the transient. It is worth noting, however, that the operator initiated feedwater flow reduction, and the resulting loss of coolant subcooling entering the reactor coolant channels, was the one decisive event which led to the establishment of high coolant void in the bottom of the reactor. The importance of this void in the lower part of the reactor, with respect to positive reactivity feedback, was enhanced by, a) the pre-existing neutron flux distribution which was tilted from bottom-to-top due to xenon build-up, b) the location of the automatic power regulation rods near the top of the core at the time that the positive reactivity insertion commenced and c) the slow reactivity insertion from the shutdown rods.

Based upon the results of the analysis of the Chernobyl Unit 4 reactor dynamics presented here, it is evident that the physical phenomena involved during the course of the accidents are in conformity with our existing knowledge of reactivity initiated power excursions. Although the exact details of the process whereby, and sequence in which, fuel channel failures and core disassembly occurred will remain a source of speculation, such speculation regarding this specific accident will not contribute significantly to lessons learned. If there is a lesson to be learned, it is that the most effective means of coping with a reactivity initiated transient in any reactor type, is to assure rapid and effective reactor shutdown. However, this is less a lesson learned, than it is a lesson re-learned.

REFERENCES

[1] USSR State Committee on the Utilization of Atomic Energy, "The Accident at Chernobyl Nuclear Power Plant and its Consequences", Information Compiled for the IAEA Experts Meeting, 25–29 August, 1986, Vienna.

[2] INSAG Summary Report on the Post-Accident Review Meeting on the Chernobyl Accident, 30 August – 5 September, 1986, Vienna.

CANDU Wins Engineering Award

(Staff)

Prime Minister Brian Mulroney recently presented AECL President Jim Donnelly, on behalf of the nuclear industry, with a certificate and plaque recognizing the CANDU reactor as one of the most outstanding achievements during the past 100 years. The award forms part of the celebrations marking the Centennial of the Engineering Institute of Canada. Ironically, this award was presented only a few days after the death of W.B. Lewis. Other achievements honoured included Canada's railway network and the building of the St. Lawrence Seaway.

Letters to the Editor

Dear Sir,

Dan Meneley's thoughtful article about Chernobyl (Nov./Dec. '86 issue of the *CNS Bulletin*) calls for a few comments which reinforce its main theme.

As stated in my submission to the NDP inquiry into nuclear energy (see Jan./Feb. '87 *CNS Bulletin*), if an accident of comparable severity occurred in the USSR every 20 years and if the calculated cancer mortality could not be palliated in any way, the effect would be to shorten the expectation of life in the USSR by about *half a day*. However, the general advance of living standards, a process in which energy from their nuclear reactors is obviously playing a part, is increasing the life expectancy in the USSR by about *73 days every year* compared with the year before (estimated from UN and World Bank data).

As David Myers has pointed out, the average citizen of Winnipeg is exposed to about ten times as much natural radon in the home as his counterpart in Vancouver (data from E. Letourneau). The excess radiation he receives *every two years* is about the same as that received by the average citizen of the Ukraine SSR from Chernobyl.

How long is it going to take for the scientific and professional community at least to realize that the *totality* of technological risk is negligible compared with the ordinary risks to life in the present day world?

E. Siddall

Dear Sir,

There are probably few people who would argue with Ernie Siddall's thesis that industrial development, energy use and "safety," as he has defined it, correlate well. Anyone who has visited a developing country can hardly avoid the conclusion that further development and the use of even marginally more energy would have a strong positive effect on welfare (or safety). However, to suggest, on the basis of such a correlation, that more energy will be needed *everywhere* to continue improving "safety," involves a leap of faith, at least in the case of those countries which are already highly industrialized.

The correlation indicated, in common with most other correlations, gives no insight into the chain of causation involved, and many other things could also be correlated with increased development and increased energy use, such as number of cars or televisions per capita. It is surely at the disaggregated level that one would have to look for the more basic reasons underlying any correlation of energy use with safety. At this level, one would find a great number of specific activities affecting individuals, each of these activities having both a direct impact on the safety or welfare of individuals, and an indirect impact through their contribution to overall wealth creation. A non-specialist in these matters, such as I, might view overall safety or welfare as just a huge composite of the effects of all such activities distributed in some way over all the people.

It isn't clear what the safety impact of each of these activities is. An extreme example will show this: it takes energy to build and run hospitals, but it also takes energy to produce alcohol and cigarettes. What is the safety return per unit energy expenditure in these two activities? Do they even have the same sign? In any event, thinking too much along these lines leads one down the false trail of an energy theory of value, and things are much more complicated and messy than that.

One of the reasons for supporting increased energy consumption in the future may well be the positive effect it will have on safety or welfare. It seems to me that the way to support such an argument is not to invoke "past is prologue" correlations but to try to show the effect more quantitatively at a more fundamental level.

Keith Weaver

Reply

Keith Weaver's letter (above) in effect raises the point that "diminishing returns" in respect to safety improvement are a factor in the advance of our civilization. We do the easy and cheap things first, and the going gets progressively tougher and more expensive. The safety benefits calculated by Myers and his colleagues and in my own 1982 paper took account of this factor and were meant to be unbiased estimates based on all available evidence and reasoning. One clear indication that returns have not diminished to zero is the great risk of being poor in Canada compared with being rich. This risk exceeds the risk from nuclear or coal fired power by orders of magnitude.

The Western world has spent hundreds of millions of dollars on research into the narrow field of nuclear risk, which has little effect on the safety of life anywhere. I look forward to seeing at least a few millions spent on research aimed at getting a better understanding of how we have achieved such a high level of safety in modern Canada (Keith's "chain of causation") and what we should do to speed up the process. This work would resolve many of the points which he raises; I would be very surprised if it supported the present conventional belief that energy development should be stifled.

E. Siddall

Correction

In the Perspective article entitled "Energy and Safety" by Ernest Siddall, which appeared in the January/February 1987 *CNS Bulletin*, 20 words of text were inadvertently dropped from one paragraph. On page 2, first column, in the second paragraph from the top, the sentence beginning "A meaningful scientific measure of safety..." should be replaced with: "A meaningful scientific measure of safety in a society is Expectation of Life. It is, of course, simply a number. However, a low expectation of life in any group is a measure of human tragedy; it represents an excessive number of deaths of children, teenagers, young adults and adults in the prime of their lives, including parents of children." The *CNS Bulletin* editors regret this inaccuracy and any inconvenience this may have caused.

CNS News

Risk Assessment Seminar Report

"The Scope of Risk Assessment" was the subject of a talk given by C.R. Bennett of AECL CANDU Operations at a seminar organized by the Centre for Nuclear Engineering, University of Toronto, on February 3, 1987. Central to Mr. Bennett's thesis is the recognition that proper management of risks in society requires a broad knowledge of those sciences fundamental to the environmental, behavioral and technological initiators of the risks. Furthermore, any meaningful proposal for the improvement of the risk topography must reflect a familiarity of the quantitative and qualitative effects of the exposure to our ambient risks.

Mr. Bennett provided a historical perspective which included a recognition of reduction in risks through the centuries and the organizational attempts to deal with them. The significant reduction in ill-health resulting from improvements in availability and quality of clean water and other public health measures was recognized.

Mr. Bennett concluded by outlining a preliminary attempt at a logical safety policy which would include the following objectives:

- Reduce the number of premature deaths each year;
- Eliminate overall cancer and heart disease;
- Reduce the number of accidents to the young;
- Have any safety expenditures reviewed by a centralized group of experts.

The overall objective should be to encourage research and teaching in this area to ensure availability of a pool of experts who would provide guidance to government and ensure rational allocation of societal expenditures on safety.

J.S. Nathwani

Nuclear (Chemical) Engineering Position Available

Applications are invited for a tenure stream position in the Department of Chemical Engineering and Applied Chemistry, University of Toronto. The appointment will be made at the Assistant Professor rank. Candidates should have a doctoral degree, preferably in nuclear engineering, and have experience in research or engineering development in one or more of nuclear chemical engineering, fusion technology, and fuel reprocessing. Further information is available concerning this position and application procedures. Applications should be addressed to Professor J.W. Smith, Chairman, Department of Chemical Engineering and Applied Chemistry, University of Toronto, Toronto, Ontario, M5S 1A4, and arrive by June 30, 1987.

PRV

A small group of people has found a 7000 foot deep hole near Sudbury, and decided that it would be a good idea to put 2000 tons of water at the bottom of it in a plastic bag in order to take a closer look at the sun. For good measure, they will want to include some air conditioning equipment, an air filtration plant to maintain clean room conditions, maybe a few computers, and an assortment of light detecting gear.

Naturally, this is not ordinary water, the hole is no ordinary hole, and the view that one would have of the sun would be anything but ordinary. As is noted elsewhere in this issue of the *Bulletin*, these technical gymnastics are all aimed at clarifying the solar neutrino question. There are good reasons why one should not do all this. It would cost a lot of money. It would most likely have no immediate practical benefit whatever. To the majority of the people who would contribute towards paying for it, even if they ever heard about the project, the whole adventure would probably have little significance. Furthermore, there is precedent for not carrying out this work: scientific research has for many years been neglected (financially) in Canada compared with other western countries, according to statistics published regularly by OECD. Our most recent Nobel Prize winner, John Polanyi, has stated that he would have to advise young people to consider pursuing their scientific careers in a country other than Canada because of this funding question. Budget cuts have apparently brought some university departments (along with their research programs) to their knees and have affected other research organizations in the country, notably the National Research Council.

Fortunately, there are also many reasons why neutrinos and other exotica should be pursued, reasons which scarcely need to be expounded to the present audience. The significance of these pursuits usually only appears in the long term, and it sometimes demonstrates that the whole pie can be greater than the sum of its pieces. When considered together, the results of a larger body of research can have clear social, economic and cultural impacts, whereas the outcome of an individual research project is often of very limited general interest or use.

Possibly, the case of the neutrino is different. In dispelling our ignorance about this evanescent entity (it is not only faster than a speeding bullet, it can leap through many billions of kilometres of lead at a single bound and emerge unscathed), we would be touching on the fields of quantum theory, cosmology, and religion.

A reason too often overlooked, and which is often the most important (although people are sometimes reluctant to admit it), is that this kind of experiment is, above all, fascinating and exciting.

One hopes that somewhere out there, another C.D. Howe will read the research proposal and then say, "Okay. Let's go."

Keith Weaver

CNS Branch Programs

Toronto Branch:

Solar Neutrino D_2O Detector

On January 29 the Toronto Branch opened its 1987 presentation series with guest speaker Dr. John J. Simpson, Professor of Physics at the University of Guelph, Ontario. He described a proposal to build a solar neutrino detector containing 1000 tons of heavy water (borrowed from AECL), to be situated in a Sudbury mine 2100 metres underground. The facility, still in the design stages, would consist of a shielded cavern 20 metres in diameter. At the centre of the cavern would be an acrylic vessel 10.5m across to hold the heavy water. The space between the cavern walls and the tank would be filled with light water. Approximately 2000 twenty-inch photomultiplier tubes would be used to detect the Cerenkov radiation resulting from the interaction of incoming solar neutrinos with the heavy hydrogen atoms in the heavy water. The reason for the great depth of the detector is to remove the masking effects of the ever present cosmic rays. The main purpose of the experiment is to solve the "solar neutrino problem." Past detection experiments, based on neutrino interaction with Cl-37, have detected only about one third as many solar neutrinos as modern solar theories would have predicted. The heavy water neutrino detector at Sudbury will have the virtue of immediate response (rather than waiting for chemical analysis), and it will be capable of detecting neutrinos associated with both muons and electrons (rather than just those associated with flow of electrons), and therefore will have an increased probability of detecting the "right" number of solar neutrinos. If the right number of neutrinos are detected with this new detector, it may mean that neutrinos undergo oscillations associated with muons and those associated with electrons thus accounting for the discrepancy with the Cl-37 results. Dr. Simpson presented a mechanical analogy to explain the process.

If the heavy water neutrino detector fails to detect as many neutrinos as theory predicts, either the detection mechanism is faulty, or the standard solar model is incorrect, or the sun is in a non-standard state in which there is a loss of equilibrium between energy production and surface energy emission. We will have to wait for the results of this and other lower energy experiments before deciding.

Our world is bathed in a sea of neutrinos. According to Dr. Simpson, there are one hundred of them in every cubic centimetre of air. Postulated by Pauli in 1931 and first detected by Fermi in 1934, neutrinos remain a somewhat elusive type of particle. With their extremely small mass and lack of electric charge they are difficult to detect, yet science has never ceased in its attempt to further characterize these particles. And it is not only for the satisfaction of academic curiosity that the quest continues. There are some practical considerations – one of which is very dear to the heart of the nuclear industry. Neutrinos, small as they are, carry away 5% of the energy released as a result of nuclear fission. Currently this energy is non-recoverable, but with the work of the University of Guelph's Dr. Simpson and his associates, we may be one step closer to realizing a very large benefit for society as a whole, by harnessing the neutrino energy released in the fission process. We wish him success in his endeavours.

J. Marczak
E. Hampton

Decommissioning Seminar Report

"Recent Experience in the Decommissioning of CANDU Prototypes" was the subject of a well-attended seminar given by Dr. E.S.Y. Tin of AECL CANDU Operations at the University of Toronto on 1987 February 23. The seminar was jointly sponsored by the CNS and the Centre for Nuclear Engineering at the University of Toronto.

Dr. Tin described the specific activities carried out in the decommissioning programs for the Gentilly-1 and Douglas Point nuclear generating stations. He outlined the various regulatory requirements to be met prior to and during a decommissioning program. The technologies available for decommissioning, such as decontamination techniques, arc-cutting, hydrolazer and scarifier, and radiation-protection techniques, were reviewed. Dr. Tin gave many interesting details on the dry-canister storage of spent fuel at the decommissioned stations. All the irradiated fuel at Gentilly-1 has been transferred to 11 dry canisters erected on the site. At Douglas Point, 47 canisters have been erected to hold the close to 24,000 irradiated fuel bundles.

Dr. Tin's talk was illustrated with numerous vivid photographs depicting actual activities performed at various stages in the decommissioning. The seminar prompted many questions from the interested audience.

B. Rouben

Toronto Branch Institute's CNS Scientific Excellence Award

As part of its campaign to increase awareness of the CNS and to foster the interest of prospective nuclear scientists and engineers, the Toronto Branch has instituted a $50 Scientific Excellence Award for high school students. The program works as follows. Rather than providing honorariums to speakers at branch meetings, each speaker will be asked to identify a Canadian high school of his or her choice which will then be offered a Scientific Excellence Award. At the school's next commencement exercises, the award and a specially commissioned certificate will be presented to an outstanding graduating student with demonstrated abilities in a scientific discipline.

With this award, the CNS will fulfill two goals. First, to several hundred people it will associate the name of the Canadian Nuclear Society with a rather proud moment in their lives, and secondly, it will provide encouragement for top scholars to pursue further studies in nuclear science and engineering. It is hoped that other branches will incorporate similar programs.

J. Marczak
E. Hampton

Conferences & Meetings

CNS Simulation Symposium

Sponsored by CNS NSED, to be held **April 27-28, 1987** in Chalk River, Ontario. For information contact: **Norm Spinks, Station 91, Chalk River Nuclear Laboratories, Chalk River, Ontario, K0J 1J0,** (613) 584-3311 (ext. 2176).

Tritium Safe Handling Course

Sponsored by Canadian Fusion Fuels Technology Project, to be held **May 4-8, 1987** in Toronto and Chalk River, Ontario. For information contact: **CFFTP, 2700 Lakeshore Rd. W., Mississauga, Ontario, L5J 1K3.**

Canadian Engineering Centennial Convention

Sponsored by CNS, CSME, et al, to be held **May 18-22, 1987** in Montréal. Eighteen papers on nuclear topics will appear in the following sessions: Power Reactors; Safety and Regulation; Unique Achievements; Fuel Cycle; and, The Future. For information contact: **Engineering Centennial Board Inc., Suite 410, 276 Saint-Jacques St., Montréal, Québec H2Y 1N3,** or A.B. Meikle, (416) 823-8040.

14th International Reliability, Availability and Maintainability Conference

Sponsored by IEEE, cosponsored by CNS et al, to be held **May 26-29, 1987** in Toronto. For information contact: **M.S. Grover, Ontario Hydro, H14-G4, 700 University Ave., Toronto, Ontario, M5G 1X6,** (416) 592-7728.

Uranium Mine Radiation Safety Course

To be held **June 1-5, 1987** in Saskatoon. For information contact: **Canadian Institute for Radiation Safety, Elliot Lake Laboratories, 7 Timmins Rd., Suite 7-15, Elliot Lake, Ontario, P5A 2R7.**

Nuclear Power Plant Aging and Life Extension

Sponsored by ASM, cosponsored by CNS, to be held **June 7-12, 1987** in Lincolnshire, Illinois. For information contact: **P.D. Stevens-Guille, Ontario Hydro, 700 University Ave., Toronto, Ontario, M5G 1X6,** (416) 592-5211.

27th Annual International Conference of the CNA and 8th Annual Conference of the CNS

To be held **June 14-17, 1987** in Saint John, New Brunswick. For information contact **CNS Office,** (416) 977-6152.

International Workshop on Mechanisms of Irradiation Creep and Growth

Sponsored by AECL, UKAEA, Ontario Hydro and CNS, to be held **June 22-25, 1987** on Hecla Island, Manitoba. For information contact: **Dr. C.H. Woo, Whiteshell Nuclear Research Establishment, Pinawa, Manitoba, R0E 1L0,** (204) 753-2311, ext. 2255.

International Symposium on Safety Aspects of the Aging and Maintenance of Nuclear Power Plants

Sponsored by IAEA, to be held **June 29-July 3, 1987** in Vienna. For information contact: **IAEA, Conference Service Section, P.O. Box 100, A-1400 Vienna, Austria.**

International Meeting on Nuclear Power Plant Operation

Sponsored by ANS, CNS, ENS and Atomic Energy Society of Japan, to be held **Aug. 31-Sept. 3, 1987** in Chicago, Illinois. For information contact: **Norman Wandke, Commonwealth Edison Co., P.O. Box 767, Chicago, IL 60690,** or Ken Talbot, (416) 839-1151.

International Topical Meeting on Probabilistic Safety Assessment and Risk Management

Sponsored by SNS, ENS, ANS, CNS et al, to be held **Aug. 31-Sept. 4, 1987** in Zurich, Switzerland. For information contact: **PSA '87, c/o ENS, P.O. Box 2613, CH-3001, Berne, Switzerland,** or F. King, (416) 592-7597.

6th Pacific Basin Nuclear Conference

Sponsored by Chinese Nuclear Society and ANS, to be held **Sept. 7-11, 1987** in Beijing. For information contact: **Chinese Nuclear Society, P.O. Box 2125, Beijing, China.**

McMaster University Symposium on Nuclear Science and Engineering

Sponsored by the CNS and by various groups on campus, the third McMaster Nuclear Symposium will be held **Sept. 30-Oct. 1, 1987** at McMaster University, Hamilton, Ontario. Papers from faculty, students, and professionals on all aspects of nuclear R&D, are welcome. Tentative titles should be submitted by **May 1**, and a 1-page abstract is requested by **August 30**. Persons attending the symposium may register for a nominal fee, while all speakers participate at no cost. For further information contact: **Dr. J.-S. Chang, Dept. of Eng. Physics, McMaster University, Hamilton, Ontario, L8S 4M1,** 416 525-9140, ext. 4924.

Workshop on Advanced Topics in CANDU Reactor Thermalhydraulics

McMaster University will be hosting the Second Workshop on CANDU Thermalhydraulics **Oct. 1-2, 1987** in conjunction with the Nuclear Symposium (above). The workshop will be of an informal nature, with the purpose of exchanging ideas on current developments in the field of CANDU thermalhydraulics. All papers will be presented by invited speakers. For information contact: **Dr. J.-S. Chang, Dept. of Eng. Physics, McMaster University, Hamilton, Ontario, L8S 4M1,** (416) 525-9140, ext. 4924.

International Conference on CANDU Maintenance

Sponsored by CNS, to be held **November 22-24, 1987** in Toronto. For information contact: **D.F. Meraw, Darlington NGS, P.O. Box 4000, Bowmanville, Ontario, L1C 3Z8,** (416) 623-6606, ext. 4218.

1987 International Waste Management Conference

Sponsored by ASME and IAEA, cosponsored by ANS, CNS et al., to be held **Nov. 30-Dec. 5, 1987** in Kowloon, Hong Kong. For information contact: **L.C. Oyen, Sargent & Lundy, 55 E. Monroe St., Chicago, IL 60603,** or Tom Carter, (416) 592-6024.

Third Topical Meeting on Tritium Technology in Fission, Fusion and Isotopic Applications — Call for Papers

Sponsored by The Canadian Nuclear Society and cosponsored by ANS, to be held **May 1-6, 1988** in Toronto. Papers are solicited emphasizing experience or experiments related to:
(1) Tritium Processing, including fuel cycles, tritium management, equipment design studies, breeding blanket design and experimentation, hydrogen isotope separation, recovery from reactors, and reprocessing plants; (2) Tritium Safety including environmental release studies and modelling, oxidation and conversion of tritiated hydrogen to water, consequences of exposure and dosimetry, biological effects, risk analysis and release probabilities; (3) Measurement of Tritium including tritium monitoring, process measurements, accountability and inventory control, and new techniques; (4) Tritium Properties and Interaction with Materials including physical and chemical properties, corrosion, mechanical properties, radiation and hydrogen effects; (5) Containment, Control, and Maintenance of Tritium Systems including laboratory and plant design, tritium waste management, remote technologies, practical experience with tritium handling, pumping and decontamination; and (6) Tritium Applications including tritium labelling, tritium tracers, commercial uses of tritium, other uses.
Deadline for 600-900 word summaries is **Oct. 15, 1987** with author notification by **Jan. 15, 1988.** Final paper deadline is **Mar. 15, 1988.** For information contact: **W.J. Holtslander, AECL—CRNL, Station 40, Chalk River, Ontario, K0J 1J0,** (613) 584-3311.

The Unfashionable Side

Deus ex Machina

In which George Bauer concludes his account of the rampant fuelling machine and the fate of Cleveland is revealed.

By the morning of the third day, chaos reigned. Enormous traffic jams choked Highway 401 and a great many official and semi-official presences were in the area. A spokesman for Energy Grope was interviewed at the site and he condemned Ontario Hydro on all counts. When asked what he thought this meant for the remainder of the nuclear program, he was quoted as saying "If their containment buildings can't isolate an eight ton fuelling machine I'm not reassured that they can do better with a quarter of a gram of iodine."

Containment analysts were quick to refute this criticism, pointing out that all the iodine is expected to be dissolved in the water and therefore be immobilized. In contrast, the fuelling machine was both mobile and unreactive and hence could easily escape through the nearest open airlock.

Meanwhile, senior Hydro management met again today to review aerial photos of the machine's progress. It was moving in a direction heading generally toward London but the significance of this was not clear. Management also had to deal with an urgent request from the AECB. This request asked that an analysis be submitted immediately demonstrating that the fuelling machine, which was carrying a full complement of discharged fuel bundles, met the requirements imposed on containers used to transport spent fuel.

It was also revealed this morning that the famous nuclear trouble-shooter, Dr. Eugene Scheuler, (affectionately known in the industry as "Scheuler") had been on the scene within six hours following the first alarm. Scheuler was also interviewed early this morning but refused to give details of his plans. "We are dealing with a deadly and highly capable machine that has extraordinary information gathering powers. I won't be giving out any information that might be useful to it" he said. However, he did outline his general philosophy of "attack in depth" which he employs in such difficult cases.

"One needs to have more than one resource available at once," Scheuler explained. Initially he had called on the armed forces for help. Unfortunately, it turned out that the tank was at its summer pasture in Petawawa, taking part in a manoeuvre called Operation Stud. It could not be transported south quickly because the Starlifter was being refitted with a larger video studio. In any case, the tank would have been of limited value since its shell was at Cold Lake being refilled.

The second string was pure Scheuler genius. He had programmed the remaining fuelling machine to hunt down and attack its twin. Alas, it was learned late this morning that this had ended in failure, but not without a close fight. It seems the second machine found its rogue sibling and began pounding at the transporter with its ram. There ensued a gripping battle, a sort of cosmic ovine fencing match. (Witnesses described it as fascinating and numbing in its power; "the rams were ramming here and the rams were ramming there" noted one, while the transporter reeled and canted under the heavy blows.) Eventually, Joe (the one that escaped) won the day by lodging several high power bundles next to Brian's video control centre. Although the machines are radiation hardened, they can not withstand fields of this magnitude and Brian's sight was gone. Thus blinded it wandered off at high speed threatening to overrun several villages and had to be taken out by mortar fire.

Late this afternoon we learned that Scheuler's final stratagem had been brought to bear: he was going into the field single handed against Joe. The first unconfirmed word to reach us was that he had succeeded in neutralizing the machine using a sling. Protected only by a thick lead codpiece he planned to approach the machine closely and hurl strong alnico magnets at it. He expected that they would be demagnetized fairly quickly in the strong fields but not before they had accomplished their objective: to erase the machine's locomotion programs stored in chips near the video control unit. Reports reaching us claim that he had succeeded in attaching five magnets to the control unit at one point which had resulted in erratic behaviour by the machine. It had roared off at speed on the transporter but lost control on a curve and flipped into a culvert. One confirming report has reached us within the past twenty minutes and spirits are rising here at the operations HQ.

All that remains now is to determine what caused this cataclysmic behaviour. With much of the machine's memory erased there is expected to be no information forthcoming from that quarter. Suspicions have been raised by fragments of data that were lodged in the station computer memory during its brief exchange with the machine. The scant data definitely does indicate that the machine had been instructed to follow a course that would have taken it to London, thence to a point in Central Hudson's Bay. Clearly this leg could only have been by air.

Is it too much to expect that the machine was heading for London airport so that it could hijack a plane? What was the nature of the rendezvous in Hudson's Bay, or was this a foil for something else? Did the heavy signals traffic picked up off Halifax have any bearing here? Was the machine's final destination really Dzerzhinsky Square?

Most probably we will never know.

George Bauer