Thin Safety Margin
Geren, Collis, Havens, Jerry

Published by University of Arkansas Press

Geren, Collis and Jerry Havens.
University of Arkansas Press, 2021.

For additional information about this book
https://muse.jhu.edu/book/98366

For content related to this chapter
https://muse.jhu.edu/related_content?type=book&id=3038644
For the fast breeder to work in its steady-state breeding condition you probably need something like a half ton of plutonium. In order that it should work economically in a sufficiently big power-producing unit, it probably needs quite a bit more than one ton of plutonium. I do not like the hazard involved. I suggested that nuclear reactors are a blessing because they are clean. They are clean as long as they function as planned, but if they malfunction in a massive manner, which can happen in principle, they can release enough fission products to kill a tremendous number of people. . . . If you put together two tons of plutonium in a breeder, one tenth of one percent of this material could become critical. I have listened to hundreds of analyses of what course a nuclear accident can take. Although I believe it is possible to analyze the immediate consequences of an accident, I do not believe it is possible to analyze and foresee the secondary consequences. In an accident involving a plutonium reactor, a couple of tons of plutonium can melt. I don’t think anybody can foresee where one or two or five percent of this plutonium will find itself, and how it will get mixed with some other material. A small fraction of the original charge can become a great hazard.

Edward Teller, 1908–2003

In September 1972, Dr. Richard E. Webb appeared before the Joint Committee on Atomic Energy of the U.S. Congress in opposition to the construction of the Clinch River Breeder Reactor Project (CRBRP). Dr. Webb testified to the potential danger of nuclear explosions in fast reactors that could be severe enough to compromise the containments then proposed to prevent catastrophic releases of radioactive materials to the environment. Webb’s testimony included statements that the AEC was
taking a chance with public safety by approving SEFOR as well as the CRBRP before sufficient research had been done to determine the maximum explosion potential that was possible in liquid-metal-cooled fast reactors. The written record of his testimony was followed by the AEC’s response, which we believe was unjustifiably dismissive. Webb prepared a written rebuttal to the AEC’s response and delivered it to the AEC in July 1973. Webb’s rebuttal was not made public by the AEC (to our knowledge), but we know the AEC received his rebuttal remarks, as the University of Arkansas Library determined that a copy of the rebuttal document is held by the Nuclear Regulatory Commission (NRC) in Washington, D.C.

We obtained a copy of Webb’s rebuttal remarks to the AEC from Purdue University, whose library holds Dr. Webb’s papers relating to nuclear safety, in 2014. After careful review, we concluded that the rebuttal remarks, which exceed two hundred pages, constitutes one of the best discussions of fast nuclear reactor safety explosion hazard potential (that could be considered understandable by the public) that was available at the time it was written—mid-1973, one year after SEFOR closed. Webb’s rebuttal “report” is particularly significant because it can be confirmed that the AEC (now NRC) received it (presumably in 1973). The rebuttal remains today an excellent example of independent-expert testimony on the specific subject of fast-reactor explosion potential.

We present here selections pertaining to reactor safety from Dr. Webb’s testimony to Congress in 1972 followed by selected sections from the AEC’s response. We then present selected material from Webb’s rebuttal, which we believe remains insufficiently considered to this day. Finally, a stand-alone section from Webb’s rebuttal entitled “Basic Theory of LMFBR Nuclear Runaway in More Detail” is presented. This section provides excellent information for understanding the limits of nuclear explosion potential in fast reactors. While Webb’s testimony and his rebuttal will be heavy sledding for the typical reader, we think it important to make it a matter of public record in this book. In our opinion, Webb’s presentations, particularly the technical discussions about the potential for nuclear explosions in fast reactors, remain the most accurate and sober description of such risks available to the lay reader. Indeed, it is suitable for careful study as groundwork for students as well as practitioners of nuclear engineering.
It is our hope that Webb’s statements to Congress and the review thereof by the AEC in 1972, along with Webb’s rebuttal in 1973, and the effective dismissal by the AEC of essentially all of the points he raised less than a year before the AEC was dissolved, will be considered appropriate for serious consideration by any party desiring to know more about this critically important subject of nuclear fast-reactor safety—including the public and students at advanced levels in related engineering and science disciplines.

The AEC was abolished in 1974. In this chapter, we consider the relevance of Webb’s submissions to the AEC regarding the fast-reactor safety debate. Dr. Webb’s statement to Congress and his rebuttal remarks to the AEC appear below.

---

**Excerpt from Hearings before the Joint Committee on Atomic Energy, Congress of the U.S., 92 Congress, Second Session, Sept. 1972: Liquid Metal Fast Breeder Reactor (LMFBR) Demonstration Plant**

**Excerpts from Statements by Dr. Richard E. Webb**


John O. Pastore  
Chairman, Joint Committee on Atomic Energy,  
U.S. Senate, Washington, D.C.

Dear Senator Pastore:

I am enclosing my statement concerning the Liquid Metal Cooled, Fast Breeder Reactor Demonstration Plant. Please accept it for inclusion in the record of your hearings on the LMFBR Demo.

My background and expertise briefly is as follows:

1. Ph.D. in Nuclear Engineering, the Ohio State University, March 1972. My Ph.D. thesis concerns the explosion potential of the LMFBR.
2. Served four years (1963–1967) with the AEC’s Division of Naval Reactors, during which my primary responsibility was for the nuclear reactor portion of the Shippingport Pressurized Water Reactor.
   a. Certificate of successful completion, Bettis Engineering School of the AEC’s Bettis Atomic Power Laboratory (1965)
   b. Reactor Plant Training (one month) at the Navy’s DIG Prototype Reactor Plant at the AEC’s Knolls Atomic Power Laboratory (1966).

3. Worked one-half year at Big Rock Point Nuclear Power Station (Boiling Water Reactor) at Charlevoix, Michigan as associate engineer with reactor engineering duties in 1967. (I was offered a position with the LMFBR Program Planning Office in 1968.)

4. B.S. Engineering in Physics, University of Toledo, 1962.

5. Presently preparing a book on criteria and procedure for establishing sound public decision with respect to civilian nuclear power at Indiana University’s School of Public and Environmental Affairs (Science, Technology and Public Policy section).

Sincerely yours,

Richard E. Webb

Enclosure: Statement on the LMFBR Demonstration Plant.

**LMFBR Demonstration Plant**

*(Statement by Richard E. Webb)*

**Summary**

The Liquid Metal Fast Breeder Reactor Demonstration Plant (LMFBR Demo) should not be built (not now at least) because the maximum explosion potential has not been scientifically determined. Because the LMFBR Demo will contain up to 1.3 tons of Plutonium and a large amount of fission product radioactivity, which absolutely must not be allowed to be spewed into the environment by a reactor plant explosion, the unknown explosion potential of the LMFBR Demo makes it imperative that the present plans for constructing and operating such a reactor be discarded in favor of further, more thorough, theoretical and experimental research into the said explosion potential. . . .
**Explosion Potential**

The “Environmental Statement” (WASH-1509, April 1972) issued by the Atomic Energy Commission for the LMFBR Demo states that the substantiation of the claim that the reactor will be safe must await the issuance of the preliminary Safety Analysis Report (PSAR) when the construction permit application is filed with the AEC. (See E.S., p. 37, 107). But it is obvious from reading the Environmental Statement that the AEC and the Joint Committee on Atomic Energy have prejudged the question of safety. For example, Congress has already authorized the LMFBR Demo and appropriated the money for it (E.S., p. 1). Furthermore, the AEC asserted in the Environmental Statement that the provisions in the reactor containment structure for “blast and missile protection within the inner barrier provide substantial margins against major potential energy release for all classes of accidents” (E.S., p. 54; emphasis added). The AEC added: “While it is impossible to postulate with precision the detailed course of accidents, including their likelihood and possible environmental consequences, it is possible to place bounds on such accidents” (E.S., p. 119; emphasis added).

These statements have no scientific foundation. Based on my knowledge of the state of the science of LMFBR explosion calculations, there is no chance that the aforesaid PSAR will substantiate such conclusions. Therefore, the construction of the LMFBR Demo should not be undertaken until after the necessary theoretical and experimental research is conducted, if such research demonstrates safety. The alternative is for Congress to recall the authorization and appropriation for the LMFBR Demo, wait for the issuance of the PSAR, and its review by the AEC and the Public, then hold public hearings on the safety of the LMFBR Demo.

The basis for my assertion is contained in my Ph.D. dissertation (thesis) which was submitted to, and approved by, the faculty authorities in the department of Nuclear Engineering at the Ohio State University. The title of the dissertation is “Some Autocatalytic Effects during Explosive Power Transients in Liquid Metal Cooled, Fast Breeder, Nuclear Power Reactors (LMFBRs),” the Ohio State University (1971). A copy of the dissertation was sent to the director of the AEC’s Division of Reactor Licensing (Mr. Peter Morris), which the Committee could borrow.
To summarize the conclusions of my dissertation, the calculational methods for determining the maximum explosion possible in an LMFBR have not been developed to include all possibilities, and their combinations, for autocatalytic phenomena during and after an initial nuclear runaway. That is, there are conceivable mechanisms by which “reactivity” can or might be rapidly “inserted” due to the motion of fuel material resulting from an initial core explosion or meltdown event. (Recall that in fast reactors, a core meltdown presents a mechanism by which reactivity can increase semi-rapidly and trigger disruptive or explosive power pulses.)\(^2\) In other words, an initial event, or series of events, might cause the reactor to feed itself a massive dose of “reactivity” which would amplify the initial runaway, or cause a very severe secondary runaway; either of which might lead to a disastrous explosion.

When the calculational methods are developed to include all possible autocatalytic effects, they would still need experimental confirmation. Moreover, as I asserted in my thesis (p. 44), the present calculation methods “have not been confirmed experimentally for power reactor designs”. For example, it has been claimed by Hirakawa and Klickman\(^3\) that the KIWI-TNT power excursion experiment (TNT stands for Transient Nuclear Tests) has confirmed the MARS fast reactor excursion computer code. (The basic theory in MARS is the Bethe-Tait theory, which is partially used in the more advanced explosion codes such as VENUS. This theory provides the reactivity feedback mechanism that ends or “shuts down” the power excursion, and thereby, limits the explosion force.) However, though the post facto MARS calculation of energy yield agreed fairly well with the KIWI-TNT measurement, the power pulse height (peak power), pulse shape, and pulse width as calculated by the MARS code are completely different than the KIWI-TNT experimental results. I used a simple thermal expansion model which excludes the basic theory in MARS that was thought to be tested (i.e., the Bethe-Tait theory), and calculated all four of the above items in excellent agreement with the experimental results.\(^4\) This strongly indicates that the inherent shutdown reactivity mechanism in the KIWI-TNT experiment was not the Bethe-Tait mechanism, but one due to the simple thermal expansion of the KIWI core; and that
agreement between the MARS value of energy releases and experimental measurement was coincidental. In support of my conclusion, Jankus stated that the “Bethe-Tait assumption is definitely unjustified” for the KIWI-TNT excursion. Furthermore, KIWI was not a fast reactor. Therefore, the KIWI-TNT explosion test has not been shown to be a confirmation of LMFBR explosion theories.

The SEFOR power excursion tests, which were performed to confirm the mitigating action of the Doppler effect for fast reactors, cannot be considered as proving out the LMFBR explosion calculational methods because the SEFOR excursions were not designed to lead to an explosion. The tests involved (1) relatively mild rates of programmed reactivity insertion, (and then the total reactivity inserted was limited to a small amount); (2) designed Doppler feedback magnitudes that were much greater than typical 1000 MWe LMFBR design values; and (3) automatic termination of the power transient by control rod scram (probably preprogrammed) to ensure against unexpected secondary excursions. Because of the strong Doppler and the limited amount of total reactivity that was inserted, the strongest power excursion tested was easily stopped with only about a 10% rise in the fuel temperature, which means that the SEFOR tests approached no threshold for meltdown or explosion. Normally in LMFBR accident calculations one assumes that the initial reactivity insertion is not limited, but is unrelenting. Thus in a real accident situation the Doppler effect alone would not be sufficient to terminate the power excursion, and the core would continue to generate energy until there is an explosive or disruptive “disassembly” of the core that finally stops the power excursion and shuts down the reactor, if one could still call a reactor destroyed a “reactor.” (Just how severe the explosion is and whether aggravated by autocatalytic effects is my main concern.)

Therefore, although the SEFOR tests were very useful in demonstrating the Doppler mitigating mechanism, and were evidently successful in that regard they provide no confirmation of explosion calculational methods. This is just as well, since there is a report which indicates that SEFOR was not designed to contain severe explosions. With one-half ton of Plutonium in the SEFOR reactor, it appears that the AEC simply took a chance with the public safety by purposely
causing power excursions, which one tries normally to prevent in power reactors, to test a safety effect (Doppler feedback) that was not beforehand demonstrated in a fast reactor power excursion. (SEFOR is now being decommissioned now that the tests are finished.) Whereas, prudence would suggest that such tests involving so much Plutonium should have been conducted only after a thorough research into autocatalytic reactivity effects was completed to establish the maximum possible accident. Then prudence would suggest that such a test reactor would be placed deeply underground just in case something was overlooked. (The EBR-I, BORAX-I, and SPERT-I reactors all suffered accidents because the power excursions were under-calculated.\(^8\) But instead, SEFOR was built above ground and may have been without explosion containment. Similarly, the LMFBR Demo would be an experiment with unknowns, involving 1.3 tons of Plutonium, and fission product Strontium-90 and Cesium-137 and the like. That is, the LMFBR Demo is simply a chance that will be taken with the health and safety of the Public if allowed to be built without a firm ground of scientific research to establish the containment design.

I mentioned so far the lack of experimental confirmation of existing calculational methods, as well as the inadequacy of the calculational methods from the standpoint of autocatalytic reactivity effects. The improved calculational methods for predicting the LMFBR explosion potential, once developed, would still require experimental confirmation, just as was done to some extent for the Doppler effect in the SEFOR tests. To be sure, fast reactor explosion tests were proposed by Nims at the 1963 Argonne National Laboratory Conference on “Breeding, Economics and Safety in Large Fast Power Reactors.”\(^9\) Nims considered the straightforward approach of simply building a prototype reactor, causing the core to meltdown, and observing the resulting explosion. Such tests would have to be repeated in a variety of ways in an effort to cover all possible or conceivable ways in which the core might meltdown. Nims indicated that the costs for such a series of tests would be prohibitive, since a series of costly reactors would have to be built, just to be destroyed. As an alternative he proposed a series of partial core meltdown experiments, short of explosion, to learn the manner in which the core would meltdown; and then with a more confident understanding of core meltdown acquired by such tests, full scale
reactor meltdown tests would be designed and performed to determine the severity of the explosions associated with the prior established core meltdown patterns.

Nims argued that this alternate scheme may provide the desired information regarding LMFBR explosion potential at acceptable cost. I would add that the development of improved calculational methods regarding autocatalytic effects, that I contend is necessary, would be of help in designing such explosion experiments. (Of course, there is the possibility that such improved calculational methods might predict with confidence that the explosion potential of LMFBRs is simply too great to ever consider building LMFBRs at all.) The LMFBR Program Plan (Volume 10, Safety) provides for studies of the necessity for such explosion testing. The Plan has adopted the alternate scheme investigated by Nims as that which is to be considered, without mentioning the more direct method of testing prototype reactors.) I have seen no results of such studies. Presumably, they are still being conducted. But regardless of their outcome, until improved theoretical methods are developed and tested by reactor explosion experiments, claims that the LMFBR containment structure is designed to contain “all classes of accidents” and that “it is possible to place bounds on such accidents” will continue to be groundless. Accordingly, if the United States is to pursue LMFBR development, we should discard the plans for a demonstration power reactor in favor of further research terminating in explosion testing, unless the theoretical research proves that LMFBRs are inherently unsafe, so that we can be assured of confining the Plutonium and other radioactivity in the event of the worst possible LMFBR accident.

(The foregoing material was submitted to the AEC for comment)

Correspondence and comment follow:

September 25, 1972.

Mr. Robert E. Hollingsworth
General Manager, U.S. Atomic Energy Commission,
Washington, D.C.
Dear Mr. Hollingsworth:

Enclosed is a “Statement on the Liquid Metal Cooled, Fast Breeder Reactor Demonstration Plant” by Richard E. Webb, Ph.D. The Committee is considering the inclusion of this statement in the public hearing record on the arrangements for construction and operation of the demonstration liquid metal fast breeder reactor. Please review the enclosed document and supply the Committee with the Commission’s comments on it.

Sincerely yours,

Edward J. Bauser
Executive Director

Atomic Energy Commission

Mr. Edward J. Bauser
Executive Director, Joint Committee on Atomic Energy,
Congress of the United States

Dear Mr. Bauser:

In accordance with the request in your letter of September 25, 1972, enclosed is the AEC staff Review of a “Statement on the Liquid Metal Cooled, Fast Breeder Reactor Demonstration Plant” by Richard E. Webb, Ph.D.

In its comments the staff addresses mainly Dr. Webb’s views on breeder reactor safety. . . . Our review indicates that from technical and legal standpoints the Statement offers no justification for reversing the AEC’s current plans for designing, constructing and operating the LMFBR Demonstration Plant.

If we can provide you with any additional information in this regard, please do not hesitate to contact us.

Sincerely,

John O. Erlewine,
Deputy General Manager
AEC Staff Review of Dr. R. E. Webb’s Statement on the LMFBR Demonstration Plant

Safety Issues Pertinent to the LMFBR Demonstration Plant

The Division of Reactor Development and Technology has under way an extensive base technology and development programs for the purpose of providing engineering and safety understanding and thus assuring the success of the LMFBR program objectives, including the Demonstration Plant. Volume 10 of the LMFBR Program covers all questions relating to the LMFBR Safety program and in particular such questions as raised by Dr. Webb, which fall in the category of hypothetical accidents and their consequences. In the area of hypothetical accidents, the safety program has as its objective the understanding of phenomena related to hypothetical events and their consequences through the conduct of extensive in-pile and out-of-pile testing as well as analytical programs which complement the experiments. This understanding will provide realistic bounds and estimates of risk so as to permit both favorable engineering selection and assessment of risk relative to alternatives and to benefits anticipated. The LMFBR base and development program will encompass a full consideration of accident situations. Finally, the construction and the operation of the LMFBR Demonstration Plant will be subject to the Commission’s regulatory requirements; as required by law, a permit or license will not issue if the Commission believes such issuance would be inimical to the health and safety of the public. The Commission’s regulatory review will, among other things, be based on the state of the technology at that time, and on the specific features of the design being considered. Some examples of work under way in the areas of most concern to Dr. Webb are:

a. In the area of calculational methods for determining the magnitude of disassembly accidents, Argonne National Laboratory has developed the two-dimensional VENUS reactor disassembly code. This code takes into consideration autcatalytic reactivity effects such as fuel motion. The main conclusion from this work so far is that it takes only a moderate pressure and a very small amount of material movement to cause the disassembly of a nuclear reactor. Thus during a hypothetical nuclear excursion, the minimum energy and thus
the generated pressures are limited by the early occurrence of disassembly. This work has been conducted by using the FFTF parameters and characteristics. As can be seen from the referenced LMFBR Program Plan, work in this area is continuing. Because of the close coupling of potential safety problems to a particular design, a specific design (the demonstration plant for example) will be used to bring into sharp focus the LMFBR safety program, including work in the area of disassembly accidents of concern to Dr. Webb.

b. The in-pile meltdown tests performed to date in the TREAT reactor indicate that the mechanical damage potential is less than that which is thermodynamically possible by two or more orders of magnitude.

Dr. Webb uses the EBR-I incident as a strong justification for his argument of the autocatalytic nature of fuel element melting. It has been established that the meltdown of the EBR-I fuel was due to fuel element bowing which because of the fuel’s structural design caused a positive coefficient of reactivity. It is this effect that caused the short period transient in the EBR-I experiment and eventually led to the meltdown. The postmortem examination of EBR-I indicated that uranium was expelled from the core. More than half of the uranium which was originally at the core center had been pushed out by melting to a position near the edge of the core. Therefore, the EBR-I meltdown incident demonstrated that this phenomenon contributed to the shutdown of the reactor instead of leading the reactor into a “runaway” condition as asserted by Dr. Webb. In fact, the importance of fuel motion as a shutdown mechanism is also evident from recent analyses (ANL’s SAS and HEDL’s MELT Accident Analysis Codes) and the results from the in-pile testing in the TREAT reactor.

The following are selected excerpts from Dr. Webb’s rebuttal to the AEC of July, 1973:

Rebuttal

The AEC letter forwarding its Staff Review concludes that my Statement “offers no justification for reversing the AEC’s current plans for designing, constructing and operating the LMFBR Demonstration Plant.” However, the AEC’s staff review provides no valid basis for this
conclusion. Indeed, the staff review does not positively deny my allegations. . . .

I will first describe basically how the LMFBR explosion hazard arises and the main problem to be solved in predicting the explosion potential. This basic theory will hopefully enable the layman to follow this evaluation, including my original statement. . . .

The Basic Theory of LMFBR Explosion Hazard

Basically, the LMFBR contains bundles of vertical fuel rods packed together to form the “core” which produces most of the heat of the reactor. A coolant in the form of liquid metal (sodium) is pumped through the core to remove the heat and transfer it to the steam-turbine systems for electricity generation. The coolant passage space within the core is the narrow space between adjacent fuel rods. In addition, the core is pierced by non-fuel “control rods,” which are used to control the nuclear reaction. Surrounding the core is a “blanket” of fertile nuclear material, again in the form of rods, which is converted to fissionable fuel (Plutonium) by the “neutron” radiation from the core. (This conversion into fissionable fuel is called “breeding.”)

The explosion hazard arises because of a phenomenon called “nuclear runaway,” which is an extremely rapid rise and fall in the reactor power to extreme peak levels that yields an explosive burst of energy before the “nuclear excursion” is terminated. (This is also called a “power excursion.”) The reactor parameter or quantity that determines whether a runaway will be triggered is the “reactivity,” and is to be controlled in order to avoid a nuclear runaway. When the reactivity is made zero, the reactor power level will remain constant; and the reactor is said to be “critical,” which is the desired condition for normal, steady, full-power operations. When the reactivity is made positive (increased), but not too high, the reactor power level will rise at a controllable rate, and the reactor is said to be “supercritical.” When the reactivity is decreased to below zero (made negative), the power level will decay or fall; and the reactor would be said to be “sub-critical.”

But if the reactivity should increase above a threshold level, called “prompt critical,” then an uncontrollable nuclear runaway will occur,
which can end in core destruction, and conceivably a disastrous explosion. During the nuclear runaway the reactor is said to be “super-prompt-critical.” Again, if the reactivity is below prompt critical, but still positive (above zero), the power level will rise relatively slow in a controlled rate due to the action of something called “delayed neutrons,” which need not be described here. (See Appendix C for a deeper insight.) As we shall see, an unchecked supercritical power transient can lead to fuel overheating and then a rise in the reactivity to trigger a super-prompt-critical power transient, or nuclear runaway.

The reactor “control rods” are the mechanical devices used to control the reactor’s reactivity. They are regulated, or moved in and out of the core of the reactor (the fuel region), to control the reactivity during normal operation, in order to control and maneuver the power level. Control rod withdrawal increases the reactivity, and control rod insertion decreases the reactivity. The control rods also have a crucial emergency function to be described shortly.

The mechanisms by which the reactivity is increased in an LMFBR accident situation are: Fuel compaction, and perhaps something called fuel “implosion”; control rod withdrawal; and sodium-coolant expulsion or voiding from the interior of the reactor core. The mechanisms for decreasing the reactivity during an accident are: core expansion; fuel temperature rise (the Doppler Effect); and control rod insertion. Increasing, or decreasing, the reactivity is sometimes referred to as “inserting” positive, or negative, reactivity, as the case may be.

The reactivity is measured in “percent” units. About .35% reactivity is sufficient to make the reactor prompt-critical for an LMFBR (and about .7% for a water-cooled reactor). In general, a 2% reduction in the reactor core volume by fuel compaction produces about ½% positive reactivity (+ ½% reactivity). Conversely, a 2% increase in the core volume by fuel expansion produces about ½% negative reactivity (− ½% reactivity insertion). Therefore, slight compaction of the core can render the core super-prompt-critical and trigger a nuclear runaway, inasmuch as .35% reactivity equals prompt-critical. Due to the coolant space in the core, the potential for core compaction is about 50%, and therefore the potential for reactivity insertion is great; although the reactivity could not increase much beyond +1% without
causing a disastrous explosion and reversal of the compaction process. Unchecked control rod withdrawal, and sodium expulsion due to sodium over-heating and boiling, can each add enough reactivity to cause a nuclear runaway, as well as fuel or core compaction.

It is the slight expansion of the core in response to the build-up of energy, and hence pressure, during a nuclear runaway that decreases the reactivity to below prompt-critical so as to terminate the nuclear runaway. (The Doppler temperature effect assists the core expansion effect in inserting negative reactivity.) Since the maximum net reactivity in a runaway will be about 1% for disastrous explosions, only the initial amounts of core expansion (about 1% increase in core volume) is needed to end even the worst nuclear runaway. If the energy generated during the runaway (called the “energy yield” or “energy released”) is strong enough, the core expansion process will take the form of an explosion. The expansion of the core due to explosion will ultimately render the reactor permanently subcritical (shutdown), if we can still call a destroyed reactor a “reactor,” as the core is “disassembled” by the explosion.

The severity of the nuclear runaway depends in part on the rate at which the reactivity increases above prompt-critical—i.e., the reactivity insertion rate. A higher rate means that more reactivity can be “inserted” before expansive pressures build up than the case of a lower reactivity insertion rate, which in turn means that more expansion is then required for terminating the runaway. But before the core can expand and reduce the reactivity, the fuel materials must first accelerate outward, which takes time and, thereby, delays the termination of the runaway beyond the point in time when the expansive pressures first appear. This time delay in expansion allows the runaway power level to continue to increase rapidly, and hence to increase the energy yield before expansion terminates the runaway. Since a higher reactivity insertion rate requires more expansion to stop the runaway, this time delay is lengthened, thereby worsening the energy yield. Any such delay is dangerous, since the energy yield could very quickly (of the order of a few millionths of a second) become extremely severe producing a disastrous explosion. Therefore, a greater reactivity insertion rate means more core expansion is needed to terminate the runaway, which in turn
Thin Safety Margin

means increased time delay before a termination, which in turn means a higher energy yield and, ultimately, a greater explosion.

There is, however, another phenomenon besides the initial reactivity insertion rate on which the severity of an LMFBR nuclear runaway accident depends, and this is called an autocatalytic reactivity effect, which is the main focus of my concerns for the LMFBR explosion hazard, and is defined as an increase in the reactivity during or after an initial nuclear runaway due to some cause which offsets the negative reactivity inserted by core expansion and the Doppler effect. If autocatalysis occurs, the termination of the nuclear runaway will be delayed, or the runaway could even be made worse by increasing the reactivity instead of decreasing it during the runaway; or if the runaway is already terminated, a second runaway could be triggered. An autocatalytic effect, then, worsens the total energy yield in an LMFBR accident and the resultant explosion.

The LMFBR has the potential for nuclear runaway and autocatalytic reactivity effects because the core contains so much concentrated fuel which is not arranged in the most reactive configuration. This is because the fuel is arranged in bundles of fuel rods (about 0.2 inch in diameter) which are spaced apart for coolant passage. About 50% of the initial core volume is taken up by these coolant passages. The coolant passages, therefore, provide space for fuel compaction. Should the fuel overheat and melt down or slump, the core can then become compacted and insert the reactivity to trigger a runaway. Since only 2% volume reduction can raise the reactivity to prompt critical, and 2% more can result in a disastrous explosion, we can see the potential ease for runaway due to core meltdown.

Strictly speaking, any spontaneous rise in the reactivity while below prompt-critical is also “autocatalytic,” as it produces a worsening power excursion, and can lead into a nuclear runaway. So, in the strict sense, any core compaction, implosion, or coolant expulsion that occur upon core overheating to increase the reactivity spontaneously are autocatalytic effects.

A core overheating and meltdown situation can be created by an “over-power accident,” which I’ll call a slow power excursion or rise, short of nuclear runaway, which heats the fuel at a greater rate than what the reactor coolant can remove; or by a loss-of-cooling accident in
which the reactor coolant slows down as it passes normally through the core (due to loss of pumping), or is expelled from the core as it is boiled, or simply drains through a pipe rupture.

The fuel motion under meltdown can be vigorous as molten and hot solid fuel is pushed by the boiling, flashing, and exploding sodium coolant, and other high pressure forces, or as the fuel is acted on by gravity. The fuel motion upon core meltdown then determines the reactivity insertion rate at prompt-critical, which could be severe. Recall that sodium coolant expulsion due to boiling is another way which reactivity can be added to trigger a nuclear runaway. Other ways include control rod ejection and dropping a fuel rod bundle into a critical core during a refueling operation. These other ways could produce a severe reactivity insertion rate as well. (Although, it is not clear that a single control rod ejection by itself could trigger a nuclear runaway; but it could induce a power excursion, and core meltdown, and then a runaway.)

(Incidentally, the LMFBR core will contain about 250 bundles of fuel rods, all bunched together; and each bundle will contain about 200 fuel rods, making about 50,000 fuel rods total in the core. The number of control rods will be about 50, although these are much larger than a single fuel rod.)

The concern for autocatalytic reactivity effects arises because of the non-uniform nature of core meltdown and expansion. If the core were uniform and expanded uniformly as the result of a nuclear runaway, there would be no question but that the expansion would reduce the reactivity and terminate the runaway without autocatalysis. But because the expansion process will be highly non-uniform (i.e., the fuel motion will be haphazard) and because of the large amount of concentrated fuel in an LMFBR (the core contains enough fuel to make ten to forty separate “critical” reactors if fully compacted), there is the valid concern that the fuel will, on its way toward overall core expansion, collect in a different super-prompt-critical configuration long enough (of the order of 5/1000 second) to amplify the initial nuclear runaway or cause a very severe secondary runaway. These autocatalytic effects due to fuel motion during or right after a nuclear runaway, then, become a matter of grave concern. For an initial runaway could add enough energy to melt the whole core and even vaporize it to explosive
pressures. Under these conditions, the motion of fuel can conceivably generate very severe autocatalytic reactivity effects ending in a disastrous explosion. For example, an initial runaway could be terminated by slight expansion of the core in the initial phase of the explosion. But because there is so much fuel that is relatively loosely arranged, the expansion of fuel in one region of the core could conceivably compact another region of the core and make the overall reactor super-prompt-critical again. This “explosive compaction” could make the “reactivity insertion rate” for the second runaway very high, because the reactivity is rising with explosive fuel velocities, which tends to produce an even greater runaway. Furthermore, with explosive compaction, the momentum of the fuel would be toward increasing local compaction, and, therefore, increasing reactivity, delaying the core expansion (shutdown) process until it can overcome the momentum, which would make the runaway all the more worse. The process is extremely complicated to analyze.

A special case of fuel motion is “implosion,” where the fuel in the core explodes or expands inward or into an inner, hollow cavity that may have been created in the core upon meltdown. Implosion is neither compaction, nor overall core expansion; but it can be autocatalytic, as it tends to bring fuel together, like compaction, and thereby raise the reactivity. Thus implosion further complicates the calculation of core behavior in an LMFBR accident to predict whether net autocatalytic behavior is possible.

The primary purpose of evaluation of LMFBR safety, given in this rebuttal, is to convey to the layman the extreme complexity involved in calculating fuel motion under LMFBR accident situations or conditions, and to show that disastrous autocatalytic nuclear runaways due to fuel motion may very well be possible, and certainly have not been scientifically investigated, and that the maximum explosion potential has not therefore been established. That is, it may very well be possible for an LMFBR to suffer a disastrous nuclear explosion, releasing a large fraction, if not virtually all, of the core’s Plutonium and fission product radioactivity into the Environment, as the science of LMFBRs is not well established in this regard.
So far, I have but touched on the Doppler effect, which has an important mitigating effect on the nuclear runaway. This Doppler effect promptly inserts negative reactivity as the fuel temperature climbs during the runaway, so as to reduce the reactivity and slow down the runaway. Without it, the explosion potential of the LMFBR would unquestionably be too high. However, the reactivity reduction potential of the Doppler effect is limited to about 1% negative reactivity, which means that autocatalytic reactivity effects conceivably could override or nullify the Doppler effect.

Another important aspect of LMFBR accidents is the “reactor scram” function, which is the rapid insertion of the reactor control rods to render the core subcritical in an emergency, and thereby avoid prompt-criticality (i.e., nuclear runaway). The SCRAM, then, shuts down the reactor so as to ensure against overheating and melting, and thus core compaction and the resultant nuclear runaway, provided that the coolant is still present to remove the “decay heat” produced by the decaying radioactivity that builds up with reactor operation. Failure to SCRAM upon detection of a core-overheat situation is expected to be the most probable way in which a nuclear runaway can occur, and the power level would remain high to effect meltdown or coolant expulsion—the main reactivity rise mechanisms.

However, once the reactor is super-prompt-critical, the control rod scram function is of no use since the runaway is extremely rapid (lasting only about 1/1000 of a second), and will be over before the control rods could be inserted appreciably. Furthermore, once the core melted-down or exploded, it seems possible that a control rod scram would not be of any help in preventing secondary nuclear runaways, as (1) the core could be so distorted as to not permit control rod insertion, since these rods are fitted into the core with little clearance; (2) the control rods themselves could be damaged or ejected by the explosion; or (3) the reactivity rise due to meltdown could override the negative reactivity “worth” of the control rod scram. In addition, there is the concern that the core could suffer overheating leading to runaway before being detected quickly enough for the SCRAM to be initiated in time to control the situation.
Finally, it is useful to compare the LMFBR with the commercial water-cooled nuclear reactor of today—the so-called “light water reactor,” or the LWR. The LMFBR is greatly different than the LWR from a core meltdown and nuclear runaway standpoint. A large LMFBR has a much higher “power density in the core at normal, full-power conditions, by about 10 times (the power density is the power produced in one unit of core volume); a much greater concentration of fuel; and a much more rapid nuclear runaway given the same reactivity rise, which is a consequence of the greater fuel concentration and the different reactor coolant. LWRs have such a low fuel concentration, on the other hand, that they are not susceptible to nuclear runaway upon fuel meltdown, even if the fuel were fully compacted, according to Forbes (a point which should be confirmed). The higher power density means that the LMFBR is all the more prone to meltdown should the core suffer coolant interruption, and in that respect is more prone to nuclear runaway. The higher power density means also that the heating due to the intense radioactivity buildup in the core is greater because the radioactivity is more concentrated. This heating, called “decay heat,” exists even when the reactor is subcritical, and can by itself under certain conditions cause meltdown and bring about nuclear runaway in the LMFBR. (For example, it is conceivable that the core could be distorted by an explosion such that it would not be amenable to cooling. Because of the decay heat, the core would melt down, even if the fission power level were negligible, and trigger a secondary explosion.) Nor does the LMFBR inherently shutdown (become subcritical) should the core lose its coolant, as is the case for an LWR. Instead, a reduction of coolant in the LMFBR core can by itself raise the reactivity and trigger a nuclear runaway as mentioned before; whereas the LWR requires the presence of the water coolant in the core to make the reactor critical, because of its low fuel concentration.

In other words the LMFBR has so much fissionable material in concentrated form that it is prone to suffer nuclear runaway and explosion accidents if the core configuration or condition is perturbed slightly. Indeed, a mild local perturbation in the core of an LMFBR could generate a strong enough over-power transient so as to melt down the entire core and lead to an even stronger nuclear runaway, the bounds of which have not been scientifically determined. Again my concern for
autocatalytic reactivity effects is that a core undergoing a nuclear runaway may possibly be capable, during an early phase of the explosion, of either compacting or imploding part of its fuel so as to amplify the initial nuclear runaway or to trigger stronger secondary nuclear runaways that end in a disastrous explosion. Core explosion is given the name “core disassembly,” although this term could imply relatively nonviolent core disruption or expansion as well. Core disassembly is the reverse of compaction or implosion and eventually stops the nuclear runaway by virtue of the fact that the fuel is blown apart so that it can no longer sustain an atomic fission chain reaction to generate energy. But, if the energy created by the runaway is great enough, the disassembly would occur explosively. It is crucial to predict the fuel motion during the accident to determine whether the fuel will implode or compact in an autocatalytic manner, or whether the fuel disassembles permanently without chance for re-assembly into a critical mass, and runaway, later on.

Complicating a prediction of the motion of fuel, and thus the strength of nuclear explosions (I shall use the term “nuclear explosion” to denote the combination of the nuclear runaway and the explosion which follows.), is the existence of a myriad of different pressure sources, such as sodium coolant boiling, which can itself be explosive, gaseous by-products of the fission process, and fuel vapor and other effects, all of which are inter-related and dependent on the conditions of the reactor at the onset of trouble. These complications, plus the difficulty in predicting theoretically whether autocatalytic reactivity effects due to the complicated fuel motion can occur, and then confirming the theoretical predictions experimentally, is the central problem which my Statement, and this Rebuttal of the AEC’s comments, address.

Finally, we present Appendix C of Dr. Webb’s rebuttal to the AEC. Webb suggested (in his rebuttal remarks above) it be referred to “for a deeper insight.” It appears that Appendix C would still be lying in a drawer at the NRC had we not searched for the record of his submit- tal remarks to the AEC. In our opinion, Webb’s Appendix C may well be the most concise, accurate, and sober description of the potential explosion risks associated with fast-breeder reactors that is suitable for consideration by the public today.
Basic Theory of LMFBR Nuclear Runaway in More Detail

A nuclear power reactor, such as an LMFBR, generates energy or heat for eventual electric power production by the fissioning (splitting) of uranium and plutonium fuel atoms. This fissioning is caused by the interaction of fuel atoms with small atomic particles, “neutrons,” which fly around inside the reactor at great speeds. When a neutron strikes the nucleus of a fuel atom, it is likely to be absorbed and cause the atom to fission. The number of fuel atoms in the core is extremely large; and only a tiny fraction of these are fissioned in one second. Numerically, one ton of fuel in a large 1000 MW LMFBR is made up of about $2 \times 10^{27}$ atoms, i.e., 2 thousand trillion trillion atoms. In one second our 1000 MW LMFBR will fission $3 \times 10^{19}$ fuel atoms, or 3 billion trillion atoms. Hence to fission all of the fuel atoms in a ton of fuel in our 1000 MW LMFBR would require $2 \times 10^{27} \div 3 \times 10^{19} = 2/3 \times 10^8$ seconds (67 million seconds), or about 3 years. Therefore, when I speak of fissioning, extremely large numbers are involved, even though I might refer to one or a thousand fissions. Likewise, large numbers of neutrons are involved.

Each fission, besides releasing the sought after energy, releases several neutrons (2.5 neutrons per fission on the average), which are then available to carry on the process through the next fission cycle in order to sustain the fissioning rate (power level) in the reactor. However, since only one of the released neutrons is needed for the “next fission,” 1.5 neutrons per fission are extra, the difference between 2.5 and 1.0. But as we shall see next, these extra neutrons are lost to the system either by leakage or non-fissionable absorption, except for slight imbalances which give rise to power level transients, which can be slow or extremely rapid, as in an explosive nuclear runaway.

Because of the finite size of the batch of fuel in the reactor, which is called the “reactor core,” a fraction of the neutrons produced by fission are lost due to leakage—i.e., some neutrons escape the core and never return to cause fissions. Because, too, non-fuel materials exist in the core which absorb neutrons, such as structural materials and Uranium-238, used to dilute the fuel, some of the neutrons are absorbed...
Nuclear Explosion Potential in Fast Reactors

without causing fission. The result of the size and non-fuel effects is a competition between losses (leakage and absorption) and gains (fission neutrons). When these competing factors are balanced, the fission rate or power level is constant, and the reactor is said to be “critical.” In general, whenever fissionable material in a critical reactor is brought closer together (fuel compaction), the chances for the neutrons striking fuel atoms and causing fission, rather than leaking out of the core, will improve; and the neutron balance in the fission cycle tips in favor of excess neutrons available for fissioning. The extra neutrons then produce fissions which in turn produce extra neutrons, and so on as the fission-neutron cycle repeats. The result is a growing neutron population and a growing fissioning rate, and hence an increasing reactor power level. In this condition the reactor is said to be “supercritical.” In the reverse case, when fuel expands (fuel moving apart), the neutron leakage increases; and then the neutron balance tips the other way, causing the power level to decay, since less than one neutron released per fission on the average is available to sustain the next fission. In this condition the reactor is said to be “subcritical.”

The percentage difference between the number of neutrons available for fissioning and the number needed to sustain the fissioning rate at a constant level is a crucial parameter called the “reactivity.” Therefore, when the reactivity is positive, the fissioning rate grows and the reactor is supercritical; and when the reactivity is negative, the fissioning rate decays, and the reactor is subcritical. Thus, fuel compaction increases the reactivity, and fuel expansion decreases the reactivity. When the reactivity is zero, the reactor is critical. As we shall see, +1% reactivity is very strong.

There is another kind of neutron balance involving the time scale, and concerns the controllability of reactor power level increases. Foremost is the “neutron lifetime,” which is the time period between the release of neutrons from one set of fissions until these fission neutrons cause the next set of fissions (a fission cycle). The neutron lifetime is extremely short in an LMFBR—about .0000001 seconds, or one-tenth of a millionth of a second, due mainly to the fast speeds of the neutrons, which is why the LMFBR, Liquid Metal Fast Breeder Reactor, is called a “fast” reactor—meaning a fast neutron reactor. If this is all there were to fission-physics, then once a reactor was made slightly supercritical, it
A reactivity of .5% means that the number of fissions per cycle would increase by .5% with the passage of each neutron lifetime (i.e., from one fission cycle to the next fission cycle). This means that the number of fissions occurring per cycle increases, not at a steady rate, but at progressively increasing rate (i.e., “exponentially”). This is because the number of fissions in one cycle is .5% greater than the number of fissions in the immediately preceding fission cycle, and not .5% of the number of fissions in the first cycle after the reactivity was raised above zero. That is, the increase between successive fission cycles is .005 times the current number of fissions occurring per cycle. Since the increase per cycle gets larger when the current number of fissions per cycle gets larger, the growth rate of fissioning accelerates, instead of staying constant, as time progresses.

As an illustration, let us assume that the cycle produced 1000 fissions, and then compare the case of steady-rise with the exponential-rise after 10, 100, 300, 1000, and 2000 cycles, respectively, given the .5% reactivity. The following table illustrates the difference between the two cases.

<table>
<thead>
<tr>
<th>Nth Cycle</th>
<th>Steady Rise</th>
<th>Exponential Rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st</td>
<td>1,000</td>
<td>1,000</td>
</tr>
<tr>
<td>10th</td>
<td>1,050</td>
<td>1,051</td>
</tr>
<tr>
<td>100th</td>
<td>1,500</td>
<td>1,650</td>
</tr>
<tr>
<td>300th</td>
<td>2,500</td>
<td>4,500</td>
</tr>
<tr>
<td>1,000th</td>
<td>6,000</td>
<td>143,000</td>
</tr>
<tr>
<td>2,000th</td>
<td>11,000</td>
<td>20,500,000</td>
</tr>
</tbody>
</table>
From the table we see that there is little difference in the first 100 cycles. However, the number of fissions per cycle in the exponential case begins to get progressively greater than the steady-rise case, until past the 1000th cycle when the exponential rise “runs away.” This process happens extremely quick in time because of the short neutron lifetime (time period of the fission cycle). For example, there are 50,000 fission cycles in just one-thousandth of a second, or millisecond, which allows a tremendous growth in fissioning in a very short interval of time.

Let us now ask what would be the power level and energy generated after our hypothetical reactor was supercritical at .5% reactivity for one millisecond. The answer is that the power level would grow, if it were not controlled by core expansion (and fuel burn-up) to 500 billion times the 1000 megawatt full-power level designed for the reactor, starting with only a feeble 1/100 of a watt; and the energy generated during the millisecond would be 100 billion megawatt-seconds, roughly equivalent to a 25 megaton nuclear weapon explosion. Actually, the heat generated early during the transient would create pressures within the fuel to expand the fuel, which decreases the reactivity to a negative value. (Just as the fission rate grows exponentially when the reactivity is positive, the fission rate decays exponentially when the reactivity is negative. Therefore, when the reactivity is negative, the power level will quickly decay to a feeble level with the same rapidity as the runaway rise in power level.) This expansion, therefore, affects the reactivity, and the course of the runaway, and must be taken into account. When it is, an LMFBR under a .5% reactivity runaway (and no Doppler feedback) will produce an explosion of the order of 1000 lbs. TNT equivalent, excluding autocatalytic reactivity effects, according to estimates. This negative reactivity effect due to expansion thus terminates the runaway, limiting it to a much less violent explosion—about 1000 lbs. TNT equivalent for the assumed reactivity condition in an LMFBR. This phenomenon of exponential growth of the fission rate is called a “nuclear runaway,” which can produce a burst of explosive energy.

Given such hypothetical reactor behavior, the reactor would not be controllable, since a slight increase in the reactivity, which a reactor operator would normally want to make in order to raise the power level from shutdown to full power level, for example, would lead instantly (within a millisecond) to reactor destruction before the
control equipment could respond. This is because the mechanical reactor control equipment couldn’t make the super-fine changes in reactivity that would be needed to raise the reactor power level at a controlled rate for our hypothetical reactor. That is, the nuclear runaway would be over within a millisecond, before the control rods would move any appreciable amount.

Fortunately, for control purposes, a small fraction of the fission-released neutrons (about .3% to .7%) in a real reactor do not appear promptly with the fissions, but are emitted by the fission fragments with about a one second delay. The fraction of the fission neutrons which are delayed is called the “delayed neutron fraction.” If a reactor was made supercritical, but with the reactivity kept below the delayed neutron fraction, the delayed neutrons would have the effect of suppressing the growth rate of the fissioning, enabling one to control the reactor. To understand why, consider again our hypothetical supercritical reactor with no delayed neutrons.

With the reactivity positive, there would be more fission-released neutrons to cause further fissioning than would be needed to sustain the fission rate at a constant level. But by not being delayed, the extra neutrons would cause the extra fissioning within the short neutron lifetime. Hence, the fission rate would rise extremely rapidly in an exponential, runaway fashion. But if the extra neutrons were delayed by about one second, then the extra fissioning, caused by these extra neutrons, would be correspondingly delayed. The result is that the fissioning rate, or reactor power level, in a real reactor would grow slowly, over the time scale of seconds instead of 1/10 of a millionth of a second (i.e., instead of in the runaway fashion, if the reactivity is less than the delayed neutron fraction). In this state the reactor is still said to be “supercritical.” This neutron delay, then, provides enough time for the reactor control system to maneuver the power level during normal operation. When the desired power level is reached, the reactivity is returned to zero, so that the reactor will be made critical—i.e., producing power at a constant level.

However, if the reactivity is raised to exceed the delayed neutron fraction, then there will be an excess of prompt neutrons available for extra fissioning. The growth of fissioning will then occur over the short time period of the “neutron lifetime,” instead of over a long delayed period.
Hence, when the reactivity exceeds the delayed neutron fraction (about .35% in an LMFBR), a nuclear runaway will ensue in the fashion of our “hypothetical” reactor previously discussed. In this runaway condition, the reactor is then said to be “super-prompt-critical.” When the reactivity equals the delayed neutron fraction, the reactor is said to be “prompt critical,” which is the threshold for nuclear runaway. The crux of reactor control is to keep the reactivity below prompt critical, or else an explosive nuclear runaway will occur. But this is not always possible, as an accident could make the reactor super-prompt-critical.

Next, we shall summarize the phenomena which can change the reactivity, as these reactivity effects are crucial to the control and the accident behavior of the LMFBR. These phenomena are as follows:

- **Reducing the neutron leakage increases the reactivity.**
  This is accomplished by bringing fuel together (compacting fuel or adding more fuel) so that the neutrons have a better chance of interaction with the fuel atoms, rather than being lost due to leakage. A special case of compaction is implosion; e.g., when the fuel explodes into a hollow, interior cavity, while being essentially confined from exploding outward. A fuel meltdown could produce core compaction.

- **Increasing the neutron leakage decreases reactivity.**
  This is accomplished by moving fuel apart: expansion as with explosion; fuel falling away from the core; or fuel from the core being removed mechanically or carried away by the flowing coolant.

- **Increasing the neutron absorption by non-fuel material decreases reactivity; conversely, reducing such absorption increases reactivity.**
  This phenomenon is used to control the reactor once enough fuel is assembled to make the reactor critical. The control is effected by inserting or withdrawing “control rods” into and out of the reactor core. These control rods are made of non-fuel, neutron-absorbing material. Thus inserting them into the core robs neutrons that would otherwise cause fission, and thereby, decreases the reactivity. Withdrawing the control rods reduces the non-fuel absorption of neutrons and increases the neutrons available for fissioning, and thus increases the reactivity. In general, the reactor is designed so that the neutron
balance is achieved when the control rods are withdrawn to the “critical height” position that is part way out of the core. When the control rods are withdrawn to this height, the reactor will be critical. Further withdrawal will make the reactivity positive, and the reactor will be supercritical. If the control rods are withdrawn too far, the reactivity can increase beyond the delayed neutron fraction, and the reactor will be made super-prompt-critical, and then a nuclear runaway will ensue. These control rods are regulated so as to raise and lower the reactor power level for normal operation while keeping the reactivity below prompt critical. Also, as the fuel “burns-up” with use (each fission destroys a fuel atom), the reactivity would tend to become negative (i.e., make the reactor subcritical) since fuel burn-up has the effect of removing fuel. (A subcritical reactor could not produce power because the power level would decay to practically zero.) To compensate for this burn-up effect, the control rods are withdrawn slowly over the period of months as the fuel is depleted to keep the reactor critical and producing power. The fuel will continue to be depleted with reactor operation until the control rods are fully withdrawn from the core, in which case the reactor power level could not be sustained for normal operations (end of life), and the reactor would have to be “refueled.” However, if the reactor suffered fuel meltdown in the “end-of-life” condition, there is still the reactivity rise potential due to core compaction and, therefore, the potential for nuclear runaway accidents. The control rods also have a crucial safety function. In the event that the reactor should reach a dangerous reactivity condition (near prompt critical) the “protection system” is designed to rapidly insert or “scram” the control rods to render the reactor subcritical. This safety action is called “reactor scram.”

- *Increasing the fuel temperature decreases the reactivity.*

This is an inherent safety mechanism called “Doppler feedback,” which is being designed into LMFBR’s in the United States. It is designed to act *during a nuclear runaway* to limit the energy burst, when a control rod scram would be too slow to have any mitigating effect. More specifically, as the temperature rapidly increases in the fuel during a nuclear runaway, the Doppler effect promptly subtracts reactivity to slow the runaway and, in some mild runaway cases, can render the reactor safely subcritical until the control rod scram can permanently
shut down the reactor without the generation of excessive temperatures (i.e., explosive pressures). However, in most runaway accidents, the source of the initial reactivity increase which caused the runaway will persist to override the negative Doppler reactivity. Other sources of positive reactivity may occur as well. So Doppler feedback is not sufficient to stop most accidents. Also, the Doppler reactivity reduction potential is limited practically to about 1% of negative reactivity. Thus Doppler is not enough to cope with the potential for accidental positive reactivity addition. (The negative reactivity of overall core expansion is being counted on as the main shutdown mechanism for terminating a nuclear runaway.) The chief role of the Doppler, then, is to slow down the nuclear runaway long enough to enable the expansion process and make subcritical. This mitigating effect of the Doppler can be strong.

- Sodium coolant (liquid metal) expulsion from the core can increase or decrease reactivity, depending on which regions of the core are made devoid of coolant. This effect is due to a trade-off between increased neutron leakage and increased neutron absorption by the fuel when coolant is “voided” from the core. The net reactivity change can be positive if the sodium coolant is expelled (voided) from the inner regions of the core, where neutron leakage from the core is lowest.

Having now described the basic reactivity change mechanisms, let us learn how these mechanisms can be called into play in an LMFBR accident to bring about a nuclear runaway and explosion.

The fuel in the LMFBR is arranged in bundles of fuel rods spaced somewhat apart for coolant passage (heat removal). Therefore the fuel is not arranged in its most reactive state, since the coolant passages provide space for fuel compaction. However, the reactor fuel rods are designed to be fairly rigid so that they won’t bow inward or slump (compact) during normal operations and add excessive reactivity. However, if the fuel should over-heat, either by unchecked control rod withdrawal, which adds reactivity and causes the power level to rise to excessive levels, or by a loss-of-coolant, the fuel will melt, lose its rigidity, and could then collapse onto itself as the molten fuel moves into the coolant passage space. The result of core meltdown, then, could be
core compaction, which can cause an excessive rise in reactivity. Keep in mind that it takes only slight compaction to raise the reactivity to prompt critical—about 2% volume reduction of the core; and then slightly more compaction to trigger the nuclear runaway. That is, slight fuel movement either way can have either a serious positive reactivity effect, or a strong negative reactivity, shutdown effect. Actually, after the reactor has operated a while, intense radioactivity builds up, so that even if the reactor was made subcritical and the fission power level dropped to feeble levels, the heat from the decaying radioactivity called “decay heat,” which is substantial, will persist. This decay heating can by itself melt the fuel and could bring about core compaction.

Besides fuel meltdown, sodium coolant voiding can trigger a nuclear runaway as well. For example, a loss-of-coolant flow accident or over-power accident can lead to coolant overheating, boiling, and then expulsion or voiding of the coolant from the core. This sodium voiding can then add reactivity past prompt critical to produce a nuclear runaway. This is an example of autocatalytic behavior, where an LMFBR accident feeds itself a dose of positive reactivity by overheating to produce a nuclear runaway, which then worsens the accident.

The central concern in LMFBR accident analyses is the behavior of the reactivity during the accident. From the foregoing it is clear that besides coolant voiding we must be able to accurately predict fuel motion during an LMFBR accident situation to determine whether the explosion process itself can compact part of the core to a sufficient degree to increase the reactivity before overall core expansion permanently renders the reactor subcritical or shutdown. If sufficient fuel compaction occurs during an explosion to offset the negative reactivity due to Doppler and overall core expansion, then the net reactivity can increase, instead of decrease during the nuclear runaway, and the runaway will become worse (faster), instead of being terminated; or if the nuclear runaway had already been terminated, a second one could occur. As we’ve seen at the outset, the energy can build up very quickly to dangerous, explosive levels when the nuclear runaway condition is prolonged. The behavior of the reactor when reactivity rises instead of falls during the accident is called “autocatalytic,” meaning that the core is its own catalyst—speeding up its own fission reaction rate. Conceivably, autocatalytic reactivity
effects could even exhaust the Doppler negative reactivity effect, which would make an explosion all the more severe. Eventually, however, overall core expansion (explosion) would take over and drive the core subcritical. The question is, though, how much energy can the nuclear runaway(s) generate before being finally terminated—the energy being then correlated with the size of the resultant explosion.

The energy yield of an LMFBR nuclear runaway accident, which is the measure of the force of the explosion, is related to the rate at which the reactivity rises above prompt critical, i.e., the “reactivity insertion rate.” If the rate is low, the nuclear runaway will proceed less rapidly than otherwise, giving the fuel material time to accelerate outward (expand) and provide the offsetting negative reactivity before too much reactivity builds up to generate a stronger runaway. If the rate of reactivity increase is high, then more reactivity can be “inserted” before the expansion occurs, and a stronger runaway occurs. Remember, it takes time for fuel material to accelerate and expand, which allows for reactivity insertion. Initial meltdown events are characterized by upper limits of reactivity insertion rates of about 200% per second, which when mitigated by the Doppler effect, yields the 500 lb. TNT-order explosion, assuming no autocatalysis. But autocatalytic reactivity effects such as explosive compaction could conceivably yield insertion rates in excess of 1000% per second. Therefore, fuel motion is the primary object of study in LMFBR analyses, and must be fully understood to establish the maximum explosion potential of the LMFBR.

Complicating the nuclear runaway problem is the amount of fuel concentrated in an LMFBR, which is enough to make somewhere between 10 to 40 separate critical reactors, if the fuel is fully compacted (fully dense). Thus for example a nuclear runaway could be terminated by slight expansion of core materials during the initial phase of a nuclear runaway explosion, only to compact enough fuel later on to return the core, or a part of it, to super-prompt-critical; i.e., to trigger secondary nuclear runaways. However, with explosive compaction, the rate at which the reactivity would increase would be great, and the momentum of the compacting fuel would have to be overcome, which delays the shutdown reactivity and conceivably could enable the runaway to grow to very dangerous levels.
These factors, then, make explosive compaction a matter of grave concern. (Indeed, the atomic bomb is produced by explosive compaction [the compaction is affected by detonating a TNT charge].) Whether an LMFBR can be made to explode like an atomic bomb is a question I honestly don’t know the answer for. All I can say is that I have seen no analyses which rule out the possibility; and that I’m prevented from learning the physics of the atomic bomb, since the information is kept secret. My best judgment, though, is that the worst autocatalytic nuclear runaway in an LMFBR would not produce an atomic-bomb-like explosion, but that it may produce a severe enough explosion to “blow-up” the reactor and allow the escape of the radioactivity to the environment (the worst conceivable LMFBR explosions mentioned in this rebuttal range from 500 lb. TNT equivalent to the order of 20,000 lb. TNT, which compares with a 20,000 tons of TNT equivalent for the first A-bomb).

It is useful to compare the commercial, water-cooled reactors now being operated—the so-called light water reactors (LWRs)—with the LMFBR. The concentration of fissionable fuel in an LMFBR core is much greater than the LWR. In fact, the LWR fuel concentration is so low that without the water coolant, the fuel probably cannot be made critical even if the fuel is fully compacted. It turns out that the LWR fuel can only be made critical if the fuel is spaced apart in the form of fuel rods with water in between. Unlike the sodium coolant in an LMFBR, the water in an LWR greatly slows down the neutrons, which are released at high speeds by the fissioning. A slow neutron has a much better chance for splitting atoms than a fast neutron. Hence, a lesser fuel concentration is needed in an LWR. But if the water coolant should be expelled or drained from the core of an LWR, the reactor would be rendered subcritical, since the fission neutrons could not be slowed down, and without the slow neutrons the low fuel concentration could not sustain the fissioning. In contrast, the loss-of-coolant accident in an LWR presents the danger of a core meltdown, and the associated possible disaster of the built-up radioactivity escaping to the environment (due to the meltdown causing a breach in the reactor container). But because the LWR has a low fuel concentration, it does not have nearly the reactivity or nuclear
runaway problem associated with fuel meltdown or coolant expulsion in an LMFBR.

Further, the Doppler effect is stronger in the LWR, and the neutron lifetime is longer by a factor 1000. These facts make a nuclear runaway in an LWR less severe compared to an LMFBR for the same initial reactivity condition. (However, the LWR still has a serious potential for nuclear runaway; but this fact is beyond the scope of this LMFBR safety review.) Finally, the LMFBR has a power density in the core that is about ten times higher than that of an LWR. The power density is the amount of heat (power) generated in a given volume of core. This higher power density means that core meltdown occurs more vigorously, should adequate cooling be lost, than in an LWR. Also, the “decay heat” in an LMFBR is correspondingly stronger, which makes core meltdown worse than in an LWR without adequate cooling. This decay heat is troublesome for a number of reasons, one of which is that even if the LMFBR had shutdown (subcritical) after suffering a meltdown, the fuel might freeze into an uncoolable mass, which could soon melt again, generating the possibility of re-assembly back into a “critical mass” and nuclear runaway.

Notes


11. WASH-1101-1110. LMFBR Program Plan, August 1968. (It is presently being updated.)