THE POTENTIAL HAZARD TO SECONDARY CONTAINMENT FROM HCDA-GENERATED MISSILES AND SODIUM FIRES

Technical Report 6

February 1979

MASTER

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Prepared for:

U.S. Department of Energy
Reactor Research and Technology
Headquarters
Germantown, MD 20767

Attention: J. D. Griffith
Assistant Director for Reactor Safety

Contract EY-76-C-03-115
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SRI Project PYU-3929

Approved:

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SUMMARY

One of the primary concerns in the design of a nuclear reactor is to ensure that radioactive material will not escape from the reactor and its containment structure in the unlikely event of a hypothetical core disruptive accident (HCDA). If HCDA loads are strong enough to break the primary containment vessel and cover of the reactor, two consequences would be the generation of missiles (fragments of the primary containment vessel or cover of the reactor) and/or sodium sprays into the secondary containment building (Figure 1). If these missiles, driven by slug impact loads, have enough kinetic energy to reach and penetrate the secondary containment structure, leak paths to the environment would occur. The sodium sprays, on the other hand, may burn spontaneously and overpressurize the building.

In this report, we concentrate on the potential hazard of HCDA-generated missiles, and briefly summarize the current status of the potential hazards of sodium fires (Section IV.B). Simple analyses are performed to determine lower bounds on the HCDA energetics required to generate missiles that could reach the secondary containment structure of a 1000-MWe LMFBR. The potential missiles considered include the vessel head, components mounted on the head, and control rods (Figure 2). The analysis is divided into two parts. First, to be very conservative, we assume that none of the missiles are restrained during HCDA loading, and we estimate a conservative minimum HCDA energy required to propel the missiles up to the secondary containment structure. Second, to be more realistic, we assume simple restraint models for the missiles and estimate the HCDA energy required for the missiles to reach the secondary containment. To further simplify the analyses, we consider only the vertical motion of the missiles.

By using the REXCO code, Argonne National Laboratory (ANL) predicted the HCDA loads on the reactor core, vessel wall, and cover that result from core release energies in the range of 1600 to 5740 MW-sec. The cover loads (Figure 3) and the core loads are used in the unrestrained missile analysis. The cover loads are extrapolated for use in the restrained missile analysis.

To reach the secondary containment, an unrestrained control rod requires a core release energy of 1000 MW-sec, whereas a restrained control rod buckles under a very low load and cannot be pushed through the head and become a missile (Figure 9). An unrestrained head or head-mounted component requires an HCDA energy of 2700 MW-sec whereas the head, restrained by shear rings, requires 14,000 MW-sec. An unrestrained component mounted on a restrained head requires an HCDA energy of at least 8000 MW-sec (Figure 8). These HCDA energies are much higher than those used to provide the design loads for the primary containment structure, and consequently their probability of occurring is very remote.

The other potential hazard to the secondary containment structure, sodium spray fires, may prove to be a more serious threat. Analysis by Atomics International indicates that if enough sodium ($\sim$ 200 ft^3 Na required) is sprayed into the secondary containment building to react with all of the available oxygen, a pressure of 83 psig would be generated, much above the yield pressure of the 1000-MWe containment building (about 25 psig). Analysis by ANL indicates that during a 2500 MW-sec HCDA, about 100 ft^3 of sodium would be ejected through a single control rod opening. The generation of an 83-psig pressure will occur only if the sodium burns efficiently, a difficult process to achieve. If the sodium does not burn efficiently, the spray will settle and burn as a pool fire with a resulting overpressure of, at most, 16 psig. A pool fire is less hazardous because only a limited amount of sodium can be oxidized, and then over a long period. Studies of sodium spray fires are now focusing on their burning efficiency in typical spray configurations.

To increase the margin of safety against potential missile hazards, the cover of the reactor can be made more massive (larger areal density) so that for a given slug impulse, a lower velocity would be imparted to the cover. Also, the cover restraint mechanisms can be made stronger. To increase the margin of safety against sodium spray fire, techniques to ensure poor burning efficiency can be used and the secondary containment building may be strengthened (e.g., as suggested by ANL, using a reinforced or prestressed concrete structure).

PREFACE

This report (Technical Report No. 6[*]) presents the results of an analysis to estimate the potential hazard of HCDA-generated missiles to the secondary containment structure of a LMFBR and a review of the status of analyses performed by ANL and AI to determine the potential hazard of sodium fires. The analysis was performed at SRI International during FY 78 as part of a continuing project with DOE Reactor Research and Technology on various aspects of LMFBR safety design and analysis.

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[*] Technical reports 1 through 5 describe work performed on this contract prior to FY 78 and are not directly related to the analysis described here.

ACKNOWLEDGMENTS

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Technical support and advice was given by A. L. Florence of SRI, and by S. H. Fistedis, J. C. Bratis, and W. R. Zeuch of ANL, who provided computations of reactor loads. Analysis of sodium fire hazards was performed by H. Morewitz and M. Heisler of Atomics International, and by T. Huang and J. McDonald of G.E. Their assistance is gratefully acknowledged.

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I INTRODUCTION

One of the primary concerns in the design of a nuclear reactor is to ensure that radioactive material will not escape from the reactor and its containment structure in the unlikely event of a hypothetical core disruptive accident (HCDA). To provide this assurance, safety research is carried out to establish four lines of assurance (LOA), each of which is intended to provide an independent barrier to prevent HCDAs from occurring or progressing to the point of releasing unacceptable amounts of radioactivity to the environment.

LOAs 1 and 2 would assure that the probability of a CDA occurring is so low that these accidents can be considered hypothetical (HCDAs). However, if such accidents occur, their consequences must be understood to assure adequate design margins to protect the public.

LOA 3 would assure that the probability of rapid pressure generation in the core and subsequent damage to the primary and secondary containment structures following an HCDA is small. If, however, an HCDA were to generate loads that are strong enough to fail the primary containment vessel or cover of the reactor, two possible consequences would ensue. One of these would be the generation of missiles (fragments of the primary containment vessel or cover of the reactor) that are driven by slug impact loads. These missiles may be driven up to impact the secondary containment structure (Figure 1). If these missiles have enough kinetic energy to reach and penetrate the secondary containment structure, significant leak paths to the environment would occur.

The other consequences would be the formation of sodium sprays that would be injected into the secondary containment building, burn spontaneously, and possibly overpressurize the containment structure.

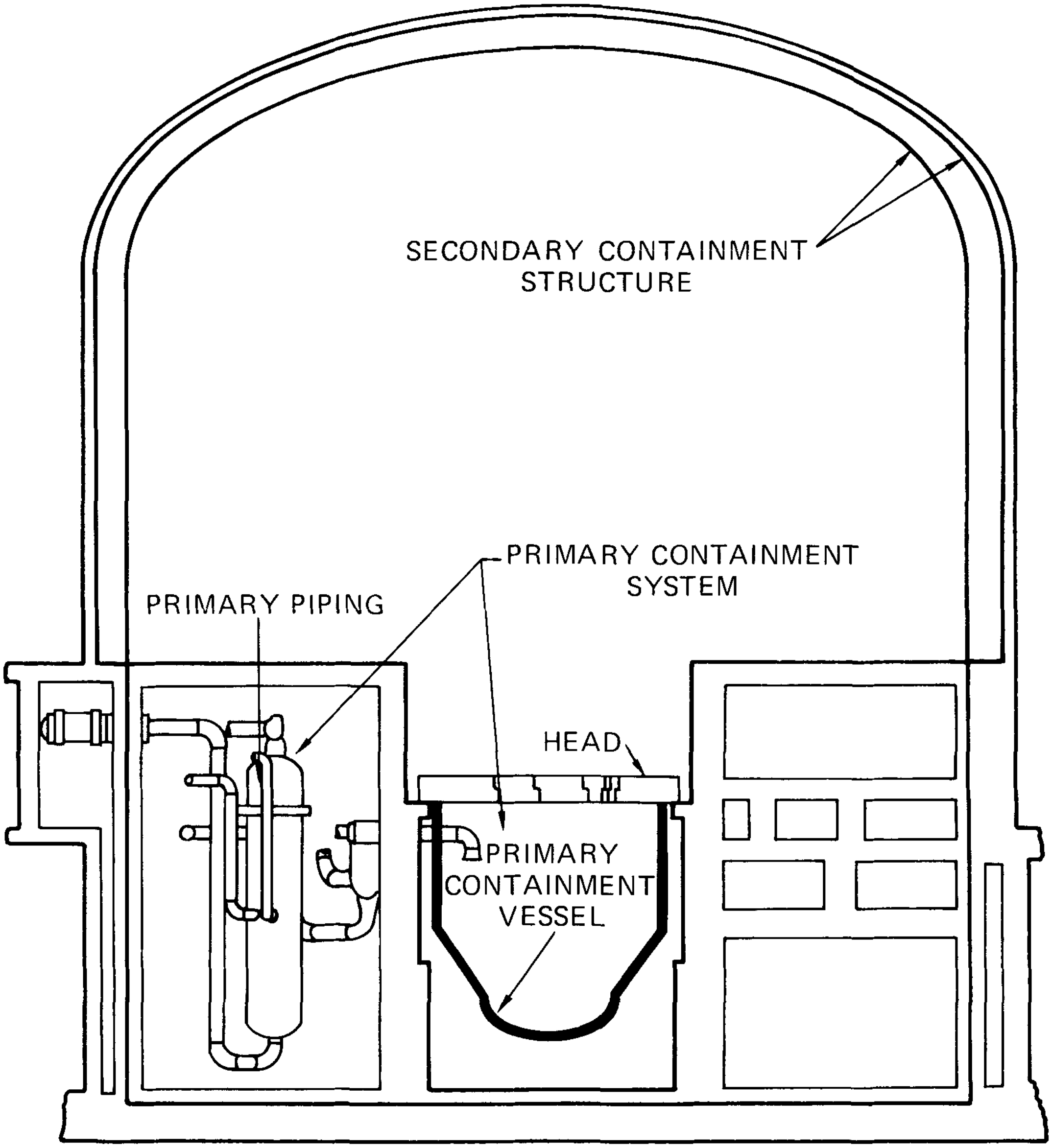

FIGURE 1 PRIMARY AND SECONDARY CONTAINMENT STRUCTURES FOR AN LMFBR

LOA 4 considers the consequences of secondary containment rupture. Research is directed to assure that there are accompanying attenuation mechanisms that would reduce potential leakage to the environment to very low levels.

Before experimental efforts can be undertaken to provide quantitative measures of the formation and potential energy of missiles during slug impact, the HCDA energetics required to generate missiles that could prove hazardous to the secondary containment structure must be determined. The objectives of the work described in this report are to provide, through analysis, bounds on the HCDA energy required to generate missiles that reach the secondary containment structure of proposed LMFBR plants, and to summarize current studies on the potential hazards of the sodium fires.

II APPROACH

The approach taken in the missile hazard assessment involves the following steps.

(1) Identification of the reactor secondary containment structure.

In this analysis, the conceptual design of a 1000-MWe reactor and secondary containment structure (Figure 1) was used [1]. The reactor has a three-plug rotating head similar to one used in the LMFBR demonstration reactor (Figure 2). The secondary containment structure includes a steel shell (1.75 inches thick) surrounded by a concrete shell 3 feet thick. The minimum vertical distance from the reactor head to the apex of the steel containment structure is 153 feet.

(2) Identification of potential missiles. Three potential missiles are considered in this analysis. The largest of the potential missiles are the three plugs of the head (Figure 2), which may break free under HCDA slug impact loads. The second potential missile is an article, such as a tool box or portable instrumentation that rests on, but is not attached to, the head. The third potential missile is a control rod that extends through the head and into the core. This rod may be ejected by the core loads and the long-term residual pressure in the reactor following an HCDA.

(3) Definition of the loads on potential missiles. The important loads are the slug impact load on the head, the core pressure acting on the above-core structure and on the control rods, and the long-time residual pressure in the reactor following an HCDA. These loads were predicted for the 1000-MWe reactor by Argonne National Laboratory using the REXCO code. The head loads are reported in Reference 2 and the core and residual pressure loads were obtained from ANL through private communications in March 1978. The slug impact loads on the head are shown in Figure 3 as a function of HCDA energy.

(4) Determination of the velocities of missiles that leave the reactor and the maximum height they achieve. Because only vertical motion is considered, the only parameter that affects the height reached by a missile is its velocity on leaving the reactor. The analysis of missile motion is divided into two parts. First, we estimate the lowest HCDA energy required to produce a hazardous missile, assuming each missile is

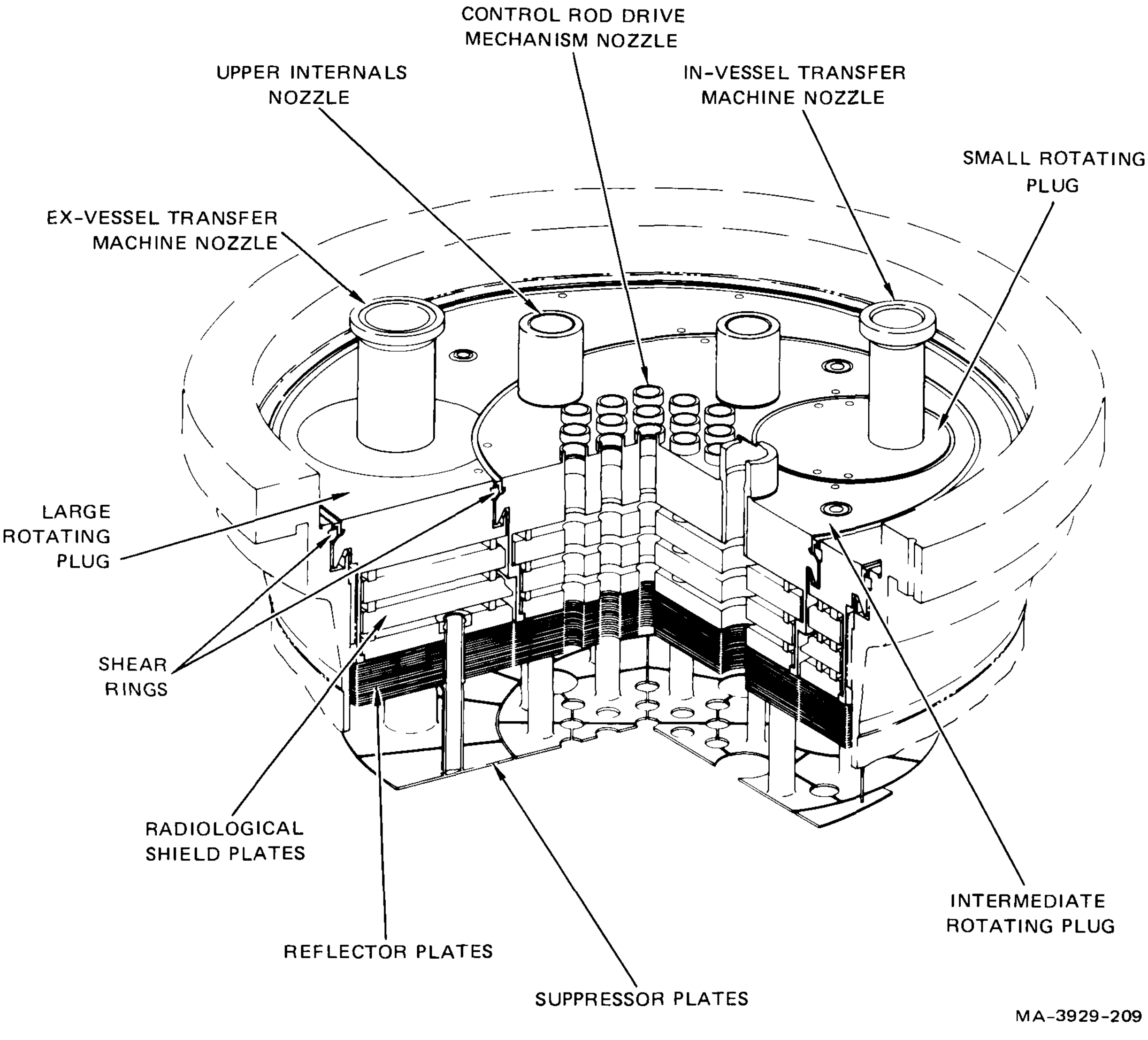

FIGURE 2 TYPICAL LMFBR ROTATING PLUG HEAD DESIGN

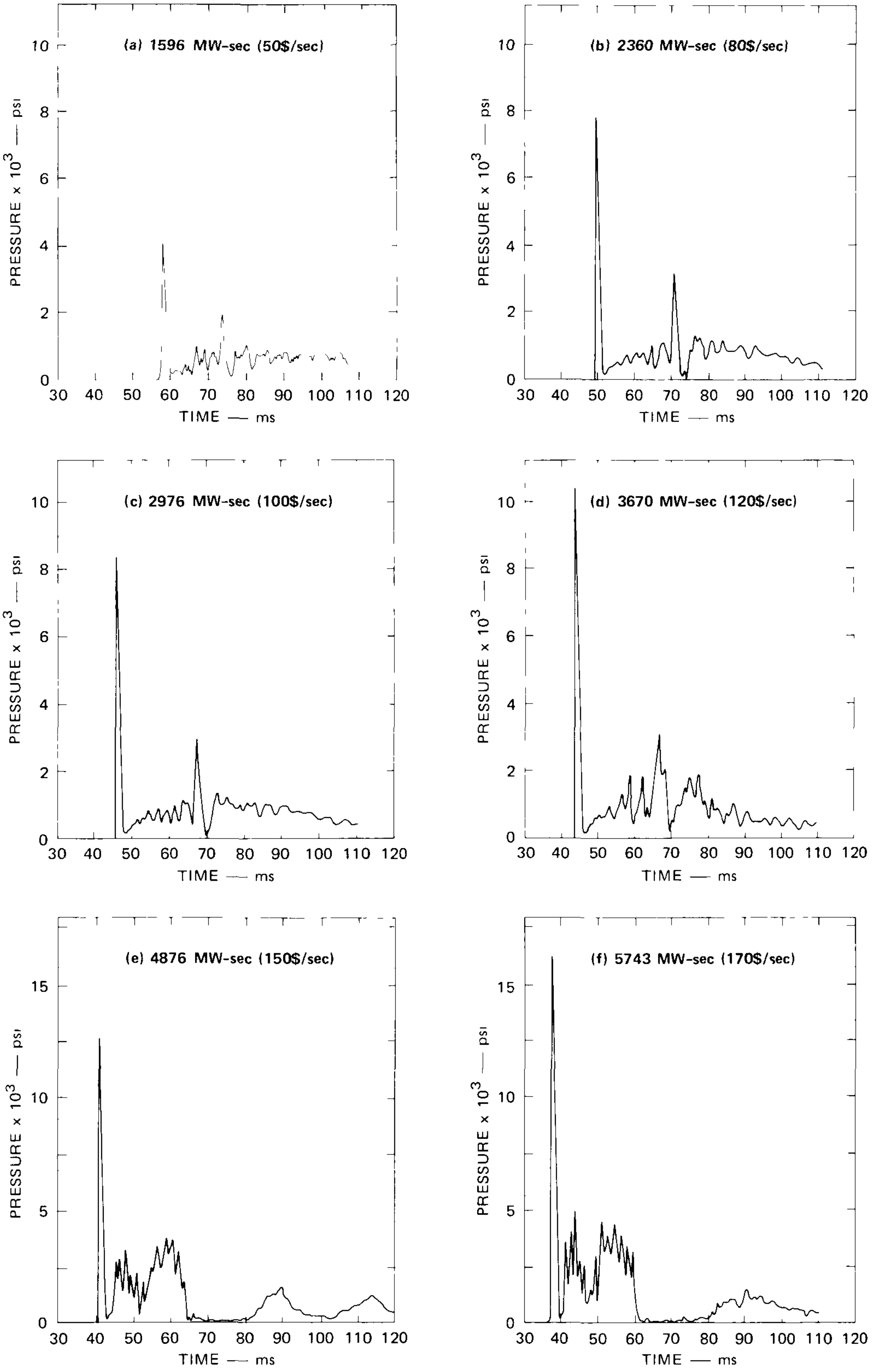

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FIGURE 3 AVERAGE SLUG IMPACT LOADS FROM REXCO ANALYSIS OF 1000-MWe REACTOR unrestrained. That is, there are no shear rings to resist upward motion of the head plugs, no restraints or hold-down mechanisms on the control rods, and the components mounted on the head are unattached. Second, a more realistic analysis is performed where simple but reasonable restraint models are developed for the missiles.

(5) Establishment of a failure criterion for the secondary containment structure. In line with the conservative approach, in the analysis we assume that missiles that just reach the containment structure are not hazardous to the containment.

III RESULTS

A. Head Missiles

In the analysis, various combinations of the three-plug head (Figure 2) are accelerated by the slug impact loads (Figure 3) and the core loads that act on an above-core structure (ACS) that is attached to the intermediate rotating plug (IRP). For the unrestrained head, the impulses from these two loading mechanisms impart a velocity that is inversely proportional to the head mass. The dimensions and masses of the head missiles are shown in Table 1.

Table 1

DIMENSIONS AND MASSES OF HEAD MISSILES

Component	Diameter (cm)	Area (cm^2)[a]	Mass (kg)
Small Rotating Plug (SRP)	196	30,042	56,818
Intermediate Rotating Plug (IRP)	612	264,000	436,363
Large Rotating Plug (LRP)	993	480,360	772,727
Above Core Structure (ACS)	376[b]	110,989	Neglected
IRP + SRP + ACS	612	294,042	493,182
Total Head + ACS	993	774,656	1,265,909

[a] Exposed to slug impact loading.

[b] Scaled up from demonstration reactor dimensions.

The relationships used to calculate the height reached by the missiles are given by the simple equations

$$V = I/M \qquad \text{and} \qquad h = V^2/2g$$

where V is missile velocity, I is impulse, M is missile mass, h is height, and g is the acceleration of gravity. Figure 4 shows the height reached by various combinations of the unrestrained head plugs as a function of HCDA energy. The lowest energy required for an unrestrained head component, or free component, to reach the secondary containment structure, which is 153 ft above the reactor head, is 2700 MW-sec.

Figure 5 illustrates the model used in the analysis of the motion of a restrained head component. The model considers shear deformation of the shear ring lip. The shear ring does not fail, because through hardening, it is a much stronger material than the shear lip. The driving force acting on the head and producing a shear zone is the slug impact pressure, P(t), which is assumed to be constant during the shearing process. Figure 6 shows the constant pressure approximation of the head load for a 2360 MW-sec HCDA.* The resisting force is derived from the shear yield stress (assumed constant) that acts on the shear area. The motion of the head is governed by the solution of the simple differential equation:

$$M_p \ddot{x} = P(t)A - \pi D \sigma_s (H - x)$$

where M_p is the plug mass, x is the displacement P(t) is the slug load, A is the area of the plug, D is the plug diameter, σ_s is the shear yield stress, and H is the initial thickness of the shear zone. Once the shear zone has been severed (x = H), the free body motion is calculated using the value of the escape velocity ($\dot{x}$ when x = H) and the load P(t) is assumed to be zero.† The REXCO slug loads had to be extrapolated to higher energies to complete the restrained head analysis (Figure 7). The extrapolation was facilitated by plotting the REXCO data on a log-log graph and smoothly extending the resulting curve. Figure 8 shows a graph

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*The initial pressure spike in the head loading is not considered in this approximation. The spike closes the initial gap between the shear ring and shear ring bearing surface.

†Once the head separates from the reactor, it is assumed that relief waves quickly reduce the pressure behind the head to atmospheric pressure.

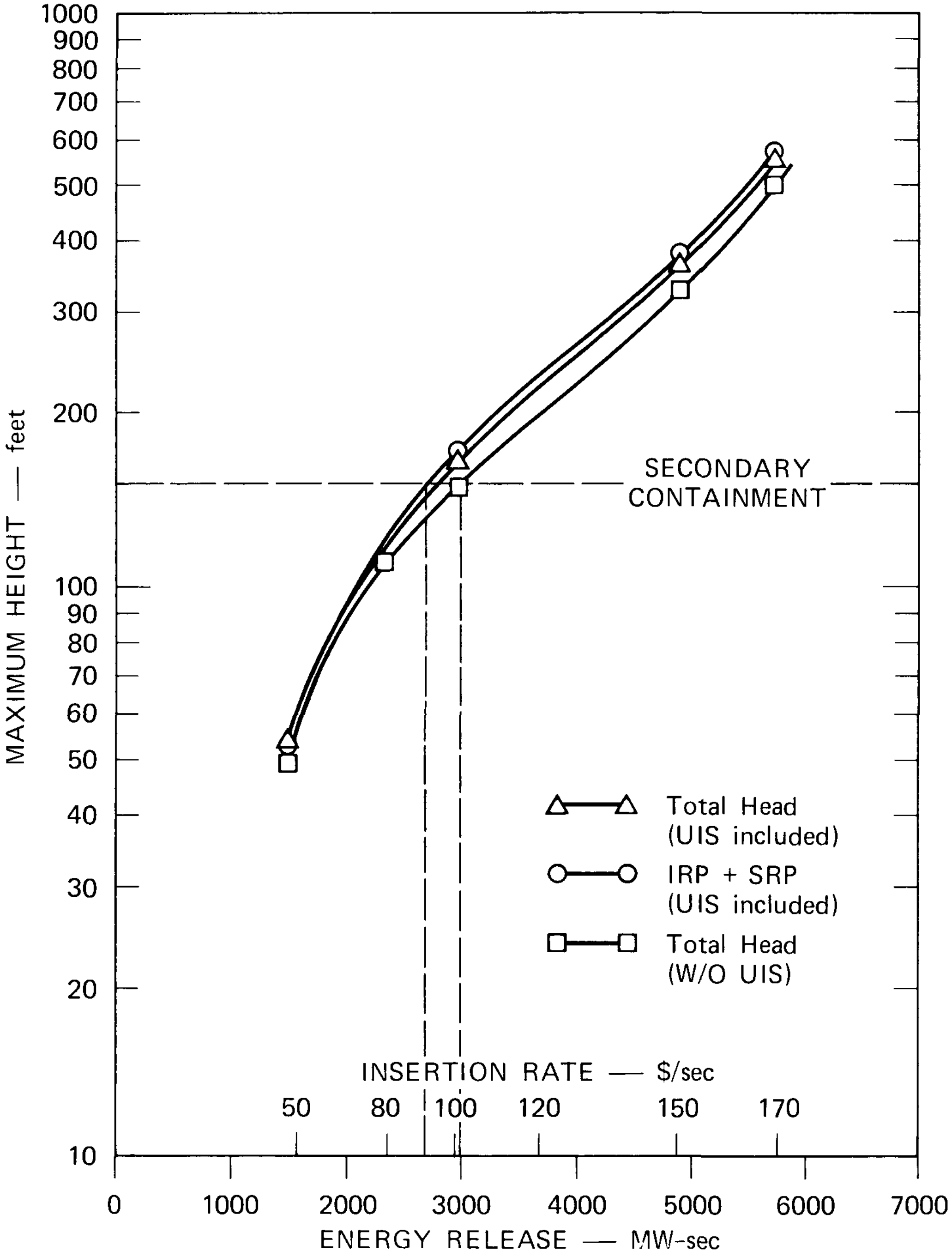

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FIGURE 4 MAXIMUM HEIGHT ATTAINED BY HEAD OF 1000-MWe REACTOR: UNRESTRAINED MODEL

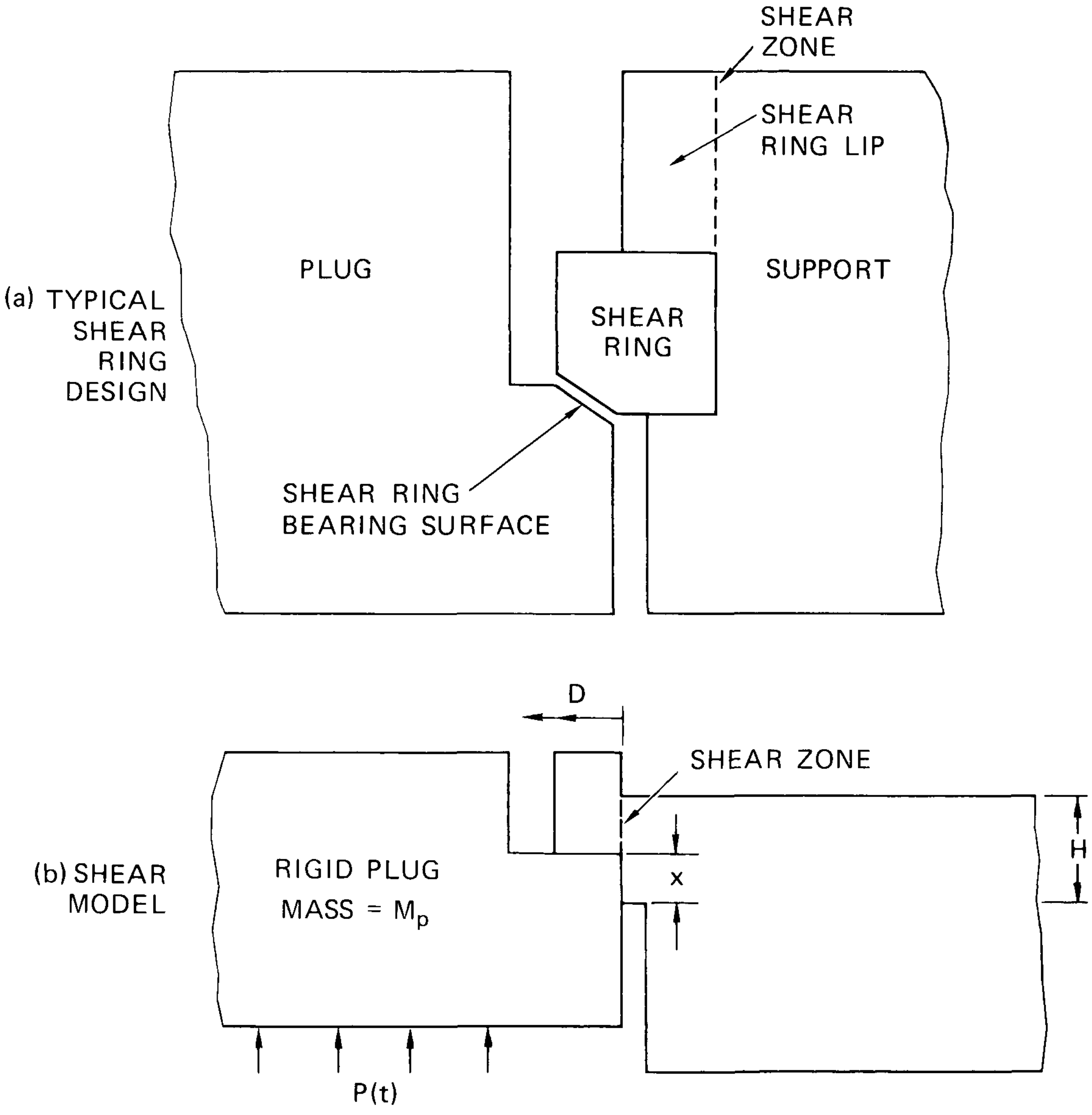

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FIGURE 5 RESTRAINT MODEL FOR HEAD

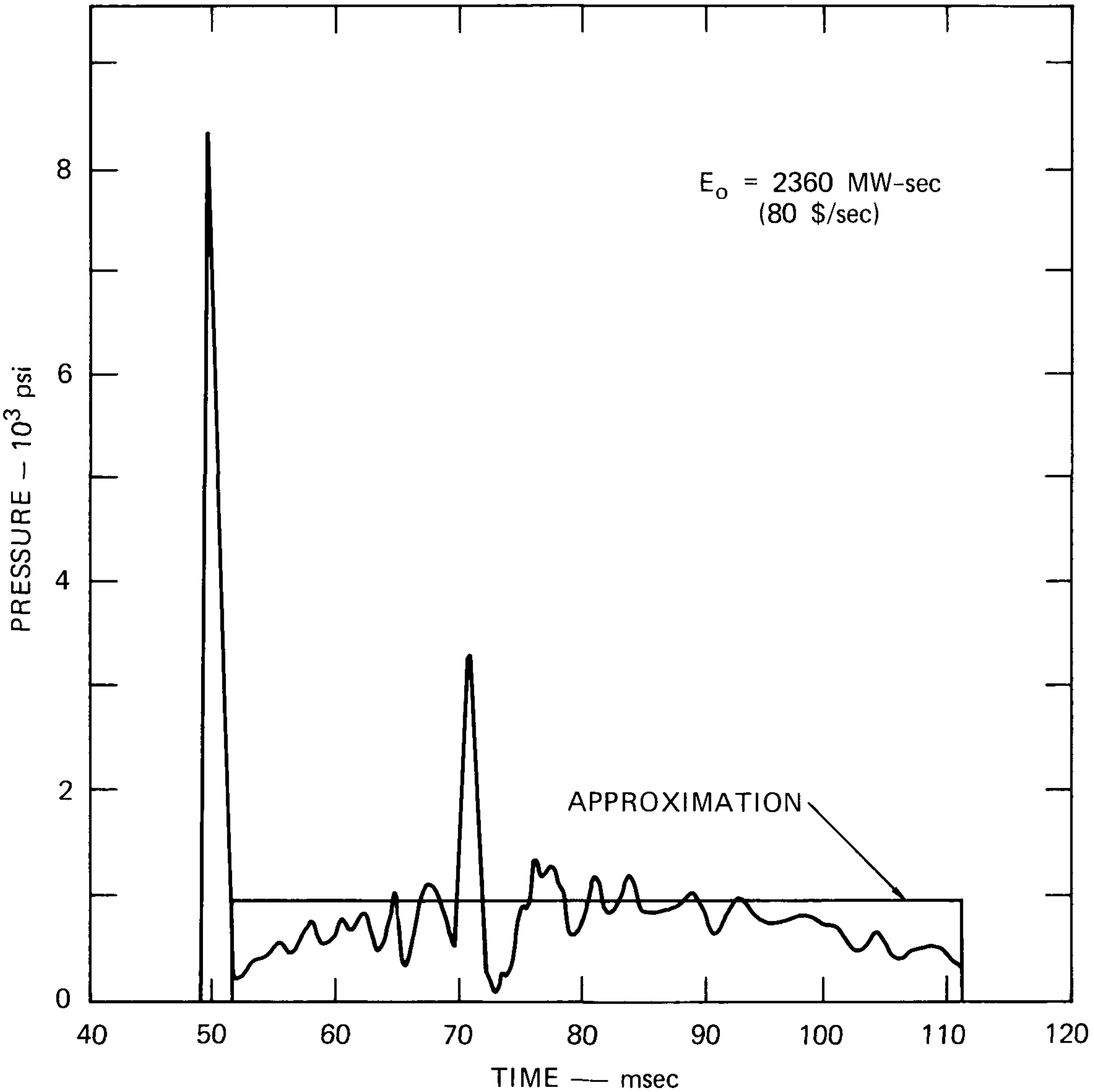

FIGURE 6 APPROXIMATION TO SLUG IMPACT LOAD FOR ANALYSIS OF RESTRAINED HEAD

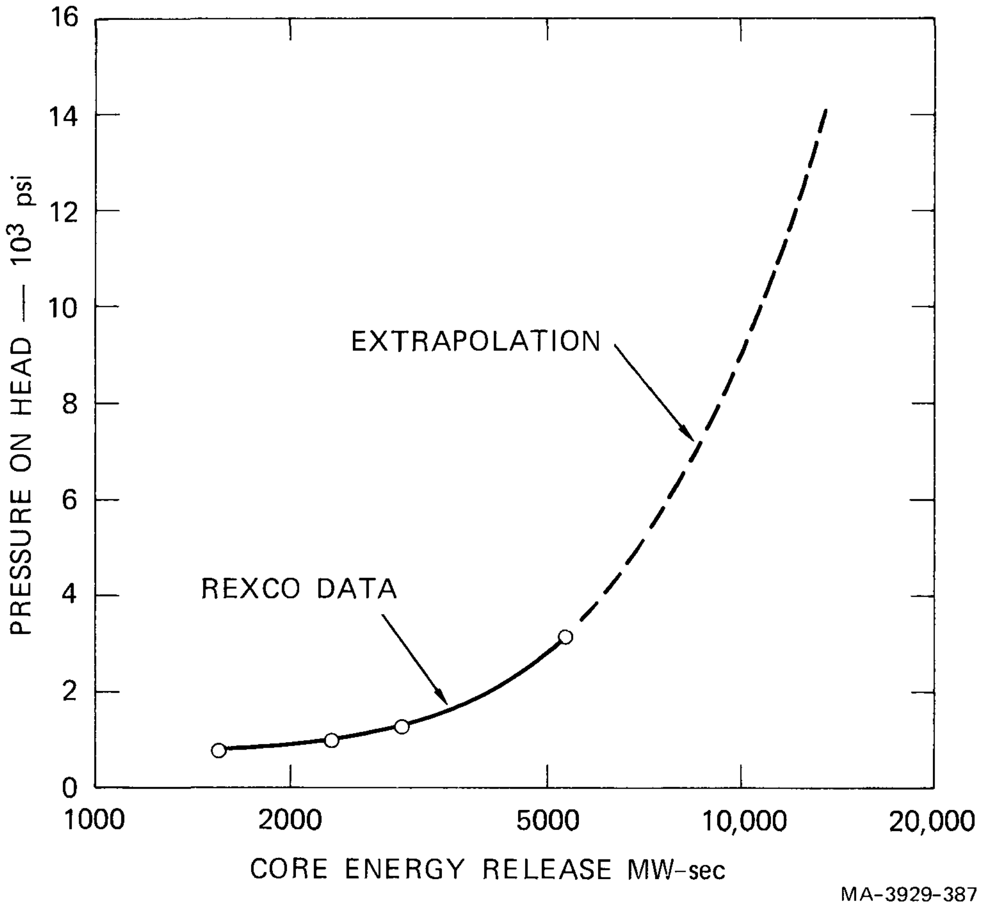

FIGURE 7 CONSTANT SLUG PRESSURE ON HEAD DURING SHEAR FAILURE PROCESS IN A 1000-MWe REACTOR

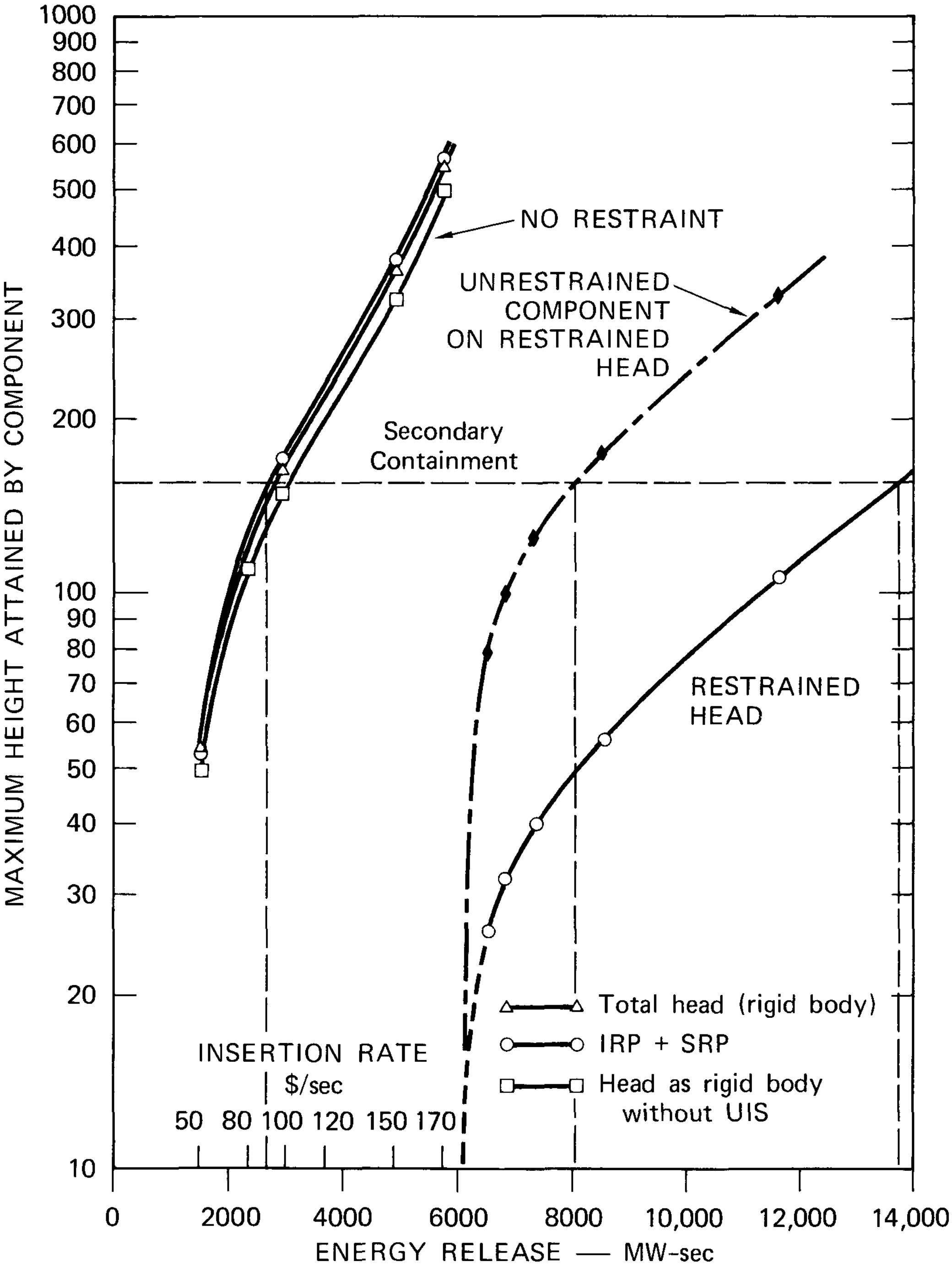

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FIGURE 8 HEIGHT ATTAINED BY HEAD OF 1000-MWe REACTOR AND BY UNATTACHED COMPONENTS ON HEAD of the missile height as a function of HCDA energy. For comparison, the results of the unrestrained head analysis are also shown. The curve labeled "component" in Figure 8 shows the height reached by an unrestrained component mounted on the restrained head. Initially, the component separates from the head when the head is decelerated momentarily during the shearing process. When the shear lip fails, the head overtakes the slow moving component and impacts it, giving the component a velocity nearly twice that of the head. Therefore, the energy required to drive a free component up to the secondary containment structure is only about 8000 MW-sec compared to the nearly 14,000 MW-sec for the restrained head.

B. Control Rods

During an HCDA, the control rods, which are long, slender columns would be accelerated first by the core pressure, which lasts only a few milliseconds, then by the residual pressure load (the equilibrium pressure in the reactor following the HCDA), which lasts several seconds. For the unrestrained missile analysis, we assume that the control rod is guided along its length so that buckling does not occur. There are no restraining forces from holddown mechanisms or from frictional forces where the control rod penetrates the head. As indicated in Figure 9, an HCDA energy of about 1000 MW-sec is required to drive the control rod up to the secondary containment structure.

Because the control rod is a slender structure it can buckle elastically before control rod restraint mechanisms fail. To demonstrate this, the control rod mechanism for a demonstration LMFBR was used in the analysis (Figure 10). The important structural features of this design include a telescoping control rod inside a shroud tube that extends over the unsupported length of the control rod (∿ 450 inches). An elastic buckling load of 144,000 lbs for the combined control rod and shroud tube was calculated from $P_{cr} = 2.05\ \pi^2 EI/\ell^2$, where the constant 2.05 is derived from the end conditions assumed fixed at the top and pinned at the bottom, $E = 30 \times 10^6$ psi, $I = 47.9$ in.^{4} is the moment of inertia for the combined control rod and shroud tube, and ℓ is the unsupported length assumed for

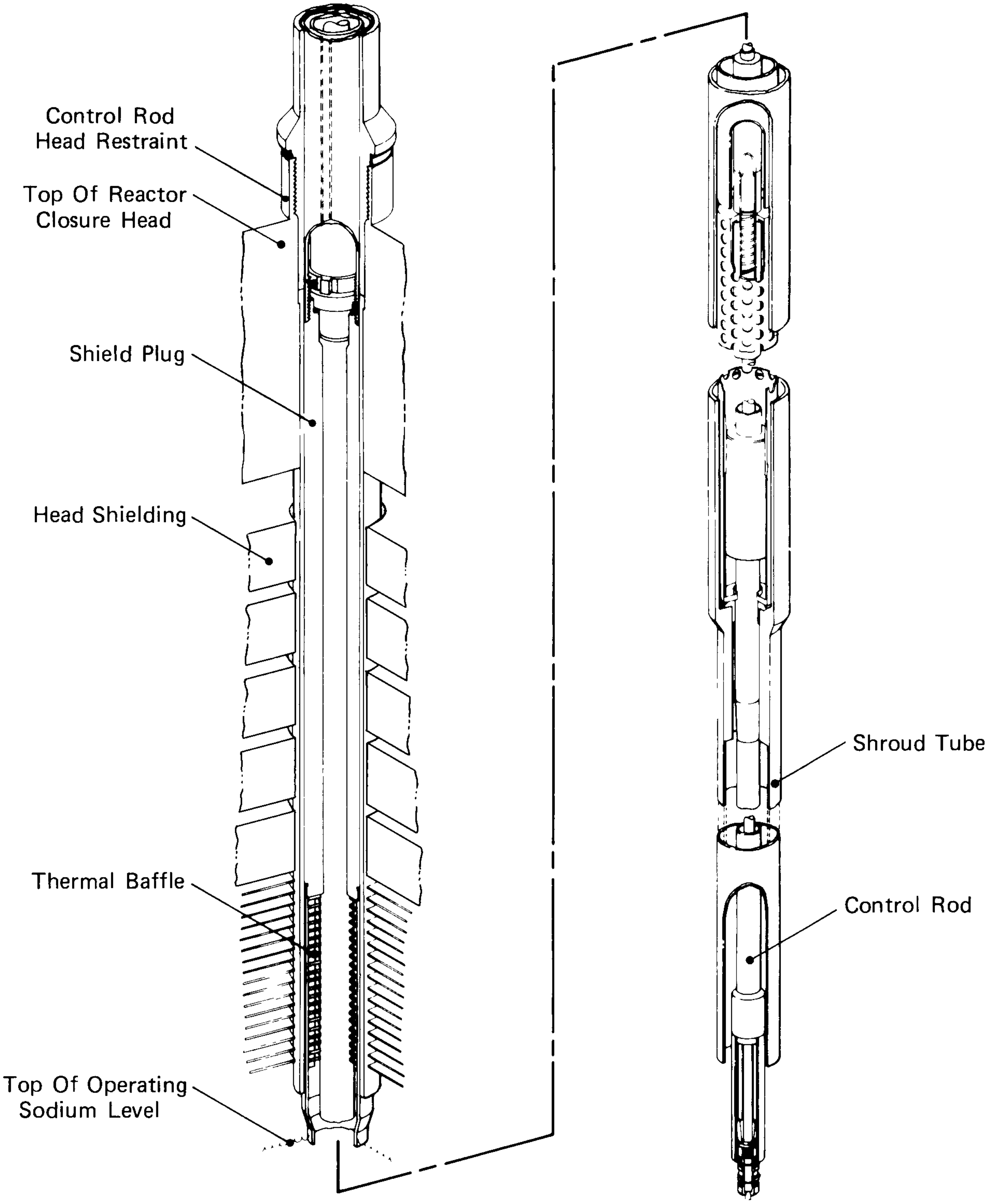

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FIGURE 10 PRIMARY CONTROL ROD DRIVELINE FOR DEMONSTRATION LMFBR the 1000 MWe reactor. Based on the demonstration plant design, a strong threaded connection in the head is capable of restraining the control rod and shroud tube beyond the buckling load. An HCDA of 1500 MW-sec produces the required buckling load. The buckled control rod cannot be forced out of the narrow penetration area through the head; therefore it cannot become a missile. This fact is noted in Figure 9 by the point on the baseline at 1500 MW-sec.

C. Reactor Size

To evaluate the effect of reactor size on the HCDA energies to produce a missile hazard, we performed an analysis using dimensions, masses, and HCDA loads for a current demonstration sized reactor. The demonstration reactor is smaller than the 1000-MWe reactor by a scale factor of 1:0.62. A notable difference between the 1000-MWe reactor design and the demonstration reactor design is that the head of the demonstration reactor is relatively thicker (more massive) than the head of the 1000-MWe reactor. In addition, for the analysis, the secondary containment building of the demonstration plant is not scaled down; it is almost identical in size and construction to the 1000-MWe containment building. The larger head mass and the relatively larger containment building of the demonstration reactor combine to reduce the potential hazard from HCDA-generated missiles.

IV SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

A. Missile Hazard Summary

Table 2 summarizes the HCDA energies required to generate missiles that may reach the secondary containment structure of the 1000-MWe reactor.

Table 2

CORE RELEASE ENERGIES REQUIRED FOR MISSILES TO REACH THE SECONDARY CONTAINMENT STRUCTURE OF THE 1000-MWe REACTOR (MW-sec)

Component	Unrestrained Missiles	Restrained Missiles
IRP + SRP + ACS	2700	14,000
Free Component on Head	2700	8000 - 14,000
Control Rod	1000	No missile

The HCDA energies presented in the table are much larger than the HCDAs used in analysis to provide the design loads for the reactor. It is more likely that the other consequence of severe HCDA loading, that of sodium spillage through leak paths in the head, provides a more serious threat to the secondary containment structure.

B. Sodium Spillage Summary

The amount of sodium ejected through the head during an HCDA is affected by: the pressure-time history of the sodium slug when it is in contact with the head, the duration of contact of the slug with the head, the size and number of the leakage paths through the head, and coefficients for head loss due to flow through constricted orifices and tortuous leakage paths. DOE called a meeting at SRI International on

4 January 1979 to review the problem of sodium spillage and sodium fires during a CDA. At this meeting, ANL presented results, obtained using the ICECO code and the 1000-MWe reactor design as a model, that indicated that during an HCDA with a core release energy of 2500 MW-sec, about 2200 kg (∿ 100 ft^3) of sodium is spilled through an opening in the head comparable to one control rod cross section during the slug impact phase of head loading [3]. Residual pressures in the reactor would force even more sodium out until the slug fell away from the head. The initial sodium is ejected with a peak velocity of about 150 m/sec (∿ 500 ft/sec). This amount of sodium sprayed into the secondary containment is sufficient to produce a pressure from 1 to 2 atmospheres when it burns, based on Atomics International (AI) estimated [4,5,6].

Representatives of AI stated that if enough sodium (∿ 200 ft^3 of sodium) were sprayed into the secondary containment building to react with all the available oxygen, a pressure of about 83 psi would be generated inside the building.* This pressure would be reached only if the sodium burned efficiently. It was further pointed out that an efficient sodium spray fire might be difficult to achieve based on some experimental evidence that indicates that a significant amount of the sodium in a spray falls to the ground and burns as a pool fire, a much less severe case. General Electric representatives pointed out that a peak pressure of only 16 psi (∿ 1 atmosphere) would be generated if 80% of the sodium in the reactor were ejected and burned as a pool fire [7]. This pressure would build up over a period of hours after the HCDA.

C. Conclusions

Because of the extreme HCDA energies required, it is concluded that vertical HCDA-generated missiles do not pose a significant threat to the secondary containment structure of an LMFBR plant. On the other hand,

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*The allowable pressure inside the building according to pressure vessel design code is 10 psi. The steel shell will yield at its base with an internal pressure of about 25 psi. A pressure of 45 psi will produce a stress equal to an assumed ultimate stress of 60,000 psi.

sodium spray fires following a severe HCDA may pose a threat to the containment building. This threat is dependent upon the burning efficiency of the sodium spray.

D. Recommendations

The potential threats of HCDA-generated missiles and sodium spray fires are largely dependent on reactor plant design. In general, the missile hazard from parts of the reactor cover can be reduced by making the head more massive or by making design details such as the shear ring assembly stronger. The hazard from sodium fires can be reduced by either making the containment building stronger or by divising mechanisms to assure poor sodium burning efficiency.

REFERENCES

1. J. S. McDonald, A. Andonedis, J. Matte III, "Liquid Metal Fast Breeder Reactor Conceptual Plant Design, 1000 MWe," joint report by Rockwell International and Burns and Roe, Inc., to ERDA-EPRI, Report No. FBR-77-3 (May 1977).

2. J. C. Bratis, W. R. Zeuch, "Energy Partitioning in Highly Energetic HCDAs: A Parametric Study," Argonne National Laboratory, reported in Progress Reports ANL-RDP-71, -72, and -74 dated May 1978, June 1978, and August 1978, respectively.

3. W. R. Zeuch, C. Y. Wang, "Sensitivity of Sodium Spillage to Accident Energetics," Argonne National Laboratory, Reactor Development Program Progress Reports ANL RDP 77 and 78 (November 1978, December 1978).

4. J. R. Humphreys, Jr., "Sodium-Air Reactions as They Pertain to Reactor Safety and Containment," Proc. of the Intl. Conf. on the Peaceful Uses of Atomic Energy, Vol. 15, p. 1893, Geneva (June 1958).

5. L. Liebowitz, "Thermodynamic Equilibria in Sodium-Air Systems," J. of Nuclear Materials, Vol. 23, pp 233-235 (1967).

6. Rockwell International, Atomics International Division, Annual Technical Progress Report No. 6 "Reactor Safety," No. ESG-DOE-13254, for Government Fiscal Year 1978.

7. T. C. Huang, A. Bayan, J. W. McDonald, J. Teresi, "Preliminary Models for Evaluating Radiological Source Terms," Topical Report GEFR-00419, General Electric Company (November 1978).