FAST BURST REACTORS IN THE U.S.A.

Thomas F. Wimett, Staff Member, University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico

1. INTRODUCTION

Historically, the development of fast prompt-burst reactors was an outgrowth of a program to determine the behavior of supercritical systems, particularly, to confirm the effectiveness of thermal expansion in quenching reactivity. The experimental behavior of the early simple versions has been used accordingly as a basis for normalizing fast-reactor-dynamics calculations.[1] While such operation comes closer than usual to damaging conditions, careful attention to operational control has resulted in the generation of many thousands of prompt bursts on the first series of fast-burst reactors without serious incident.[1]

Reactors of the first series are fabricated from highly enriched (~ 93.5% U-235) cast uranium metal and include Lady Godiva and Godiva II at Los Alamos Scientific Laboratory, Kukla and Fran at Lawrence Radiation Laboratory, and SPR I at Sandia Corporation. Near-fission-spectrum neutron bursts from these reactors have been employed in 1) basic fission studies, e.g., the extensive measurements of delayed neutron and delayed gamma parameters [2], 2) radiation dosimetry, 3) calibration of radiation alarms for criticality

[1] Two oversized bursts were experienced on Lady Godiva (which was not specifically designed as a burst reactor) as a result of errors in operational control. Damage suffered included bending of core supports, breaking of assembly bolts, and deformation of central fuel plates in the second and most extreme excursion.

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accidents, 4) radiobiology, and 5) interaction of radiation with matter such as germanium crystals [3,4], semiconductors, and biological systems.

Maximum burst yields in the first series generally are limited by fuel integrity as a result of severe shocks associated with the rapid temperature increases. Pure uranium metal, particularly as cast, is subject to surface roughening, anisotropic crystal growth, and creation of internal voids. Such effects were observed and were presumably caused by burst thermal cycling and irradiation and occurred for temperature rises (from ambient) $\sim$ 200°C -- far below the melting temperature. Mechanical shock to structural members is also a limiting factor in most of the early burst machines. (Fran is an exception as will be discussed later.)

In order to increase the fission yield per burst, efforts have been directed toward the development of cores which maintain dimensional stability when subjected to more extreme temperature cycles than may be tolerated in normal uranium metal. There also have been attempts to eliminate inertial difficulties related to the quenching delay associated with the finite time for translating fission energy into surface or volume expansion. This delay leads to an effective broadening of the bursts at a given yield. The second series of burst reactors as referred to here are those which employ an alloy of uranium, specifically 10 weight percent molybdenum (U-10 w/o Mo), in which extensive metallurgical tests have indicated relatively small crystal growth and excellent phase stability during or following repeated large temperature cycles ($\sim$ 500°C). Included in this reactor series are HPRR (Health Physics Research Reactor) at Oak Ridge National Laboratory, Molly-G or FBR (Fast Burst Reactor) at White Sands Missile Range, and Super Kukla at Lawrence Radiation Laboratory; three additional models similar to HPRR and Molly-G are in the final planning stages, one at Sandia Corporation, one at Aberdeen Proving Grounds, and one at LASL. None of these reactors has produced more than a total of $\sim$ 300 bursts to be compared with many thousands for a typical reactor of the first series. Accordingly, such devices may be considered in a relatively early stage of development.

2. PROCEDURE FOR BURST GENERATION

All reactor systems discussed here, except where noted, employ the same basic procedure for prompt burst production, namely: 1) establishment of the delayed critical control rod positions by low power operation with the burst rod withdrawn; 2) retraction of the safety block to permit decay of delayed neutron precursors born during the steady-state operation; 3) reinsertion of the safety block followed shortly by the rapid insertion of the burst rod (worth ~ 1$ excess reactivity) to boost the reactivity to the predetermined super-prompt-critical value; 4) automatic withdrawal (scram) of safety block and rods triggered by detection of power level in the burst. If an external neutron source is used during the steady-state operation, it is generally withdrawn to a less effective position during the burst mode in order to minimize "preinitiation", or the generation of a burst before maximum excess reactivity is attained by the burst rod.

3. REACTOR DESIGNS AND DESCRIPTIONS

Table I lists startup dates for the burst reactors considered here together with some pertinent characteristics. The first three are not in operation currently, but are included for historical interest.

Lady Godiva and Kukla

Lady Godiva [3,5], designed and constructed by Los Alamos Scientific Laboratory, was basically spherical in shape ~ 6.8 in. diameter with two horizontal parting planes to permit disassembly into three roughly equal sections for large shutdown effectiveness. Kukla [6], shown in Fig. 1, was designed and constructed by Lawrence Radiation Laboratory and is similar to Lady Godiva, except that it is mechanically supported from underneath rather than by hangers as in the original, and, in addition, employs a cylindrical section (safety block) ~ 7 kg uranium to be withdrawn for shutdown. Both use motor-driven screw actuators for uranium control rods and pneumatic cylinders for high-speed actuation of the safety blocks and burst rods. The exposed uranium surfaces of Kukla are nickel-flashed and overplated with 10 - 15 mils of cadmium to eliminate corrosion and to reduce neutron room-return effects, while the surface of Godiva is bare. Total fuel mass is ~ 53 kg in each reactor. The detailed burst behavior of Kukla is assumed to be identical to that of Godiva, which is discussed in the literature.[3]

TABLE I

FAST BURST REACTORS

Reactor	Initial Burst Operation (Year)	U-235 Mass (kg)	Burst Yield (Fissions)	Burst Width (μsec)	Repetition Interval (hrs)	α_R (per μsec)
Lady Godiva	1953	50	2×10^{16}	35	~ 1	1.09
Godiva II	1957	54	2.5×10^{16}	35	~ 1	1.05
Kukla	1961	50	2×10^{16}	35	~ 1	(1.09)
SPR I (Repetitive operation)	1961	54	2×10^{16}	42	~ 1	(1.05)
Fran	1962	59	4×10^{16}	40	1 - 2	~ 0.7
HPRR	1962	97	1.8×10^{17}	48	1 - 2	0.55
Molly-G or FBR	1964	81	1.2×10^{17}	35	1 - 2	0.77
Super Kukla (Preliminary data)	late 1964	1000	$\sim 2 \times 10^{18}$	~ 950	~ 8	~ 0.05

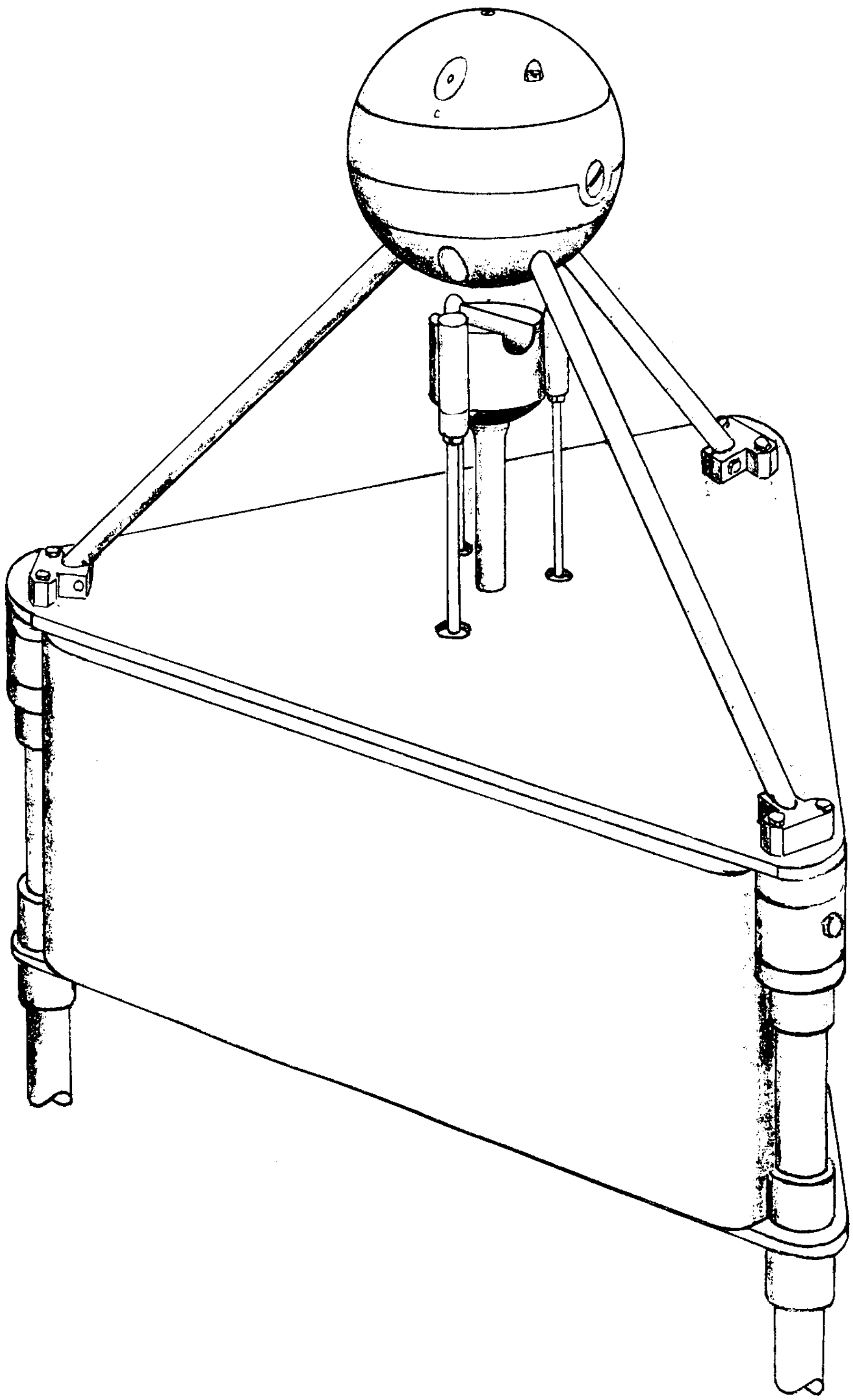

Figure 1. Sketch of Kukla showing safety block and control rods withdrawn

Godiva II

Essentially a near-cylindrical version of Lady Godiva, Godiva II [7] was designed specifically as a burst irradiation reactor with emphasis on structural stability. With temperature excursions limited to $\sim 200^\circ C$ in the region of maximum power density, about 2000 prompt bursts were produced in 3 years without observable deterioration.

As shown in the drawing of Fig. 2, the large cylindrical safety block that enters the core from underneath serves two purposes: 1) it provides a large shutdown reactivity $\sim$ 50 dollars and 2) it serves to partition the reactor along the radius in such a fashion that shock waves originating at the center are prevented from traveling to the surface of the stationary part or, stated differently, the natural period of mechanical vibration is thereby reduced. This reduction is reflected in a smaller "inertial effect".[2] To facilitate irradiation operations, the core was mounted on a small portable stand which houses all actuating machinery, control element position sensors, and electrical interlocks.

SPR I

A second model of the Godiva II core, now identified as SPR I, was fabricated at LASL for operation in the Sandia Pulse Reactor Facility (SPRF) at Sandia Corporation. The core fits with a clearance $\sim$ 1 cm inside a perforated protective screen visible in the photograph, Fig. 3. This core was nickel-flashed as was the original, and additionally was overplated with cadmium to reduce neutron coupling with the variety of objects to be irradiated externally. Experience with such reactors has demonstrated some burst lengthening as a result of neutron back scattering from massive samples placed nearby even if there is cadmium shielding. The reactor stand is supported on a hydraulically-operated elevator which lowers it into a pit after operation. A 12-inch-thick lead radiation shield slides over the pit to permit personnel entry into the building soon after a burst has been produced.[3]

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[2]As defined in [3], the inertial effect arises from the delay required for a pressure wave to travel from the interior of a fuel piece to a surface where the major reactivity quenching takes place. To first order, a delay, τ, increases burst yield by the factor $(1 + \alpha^2\tau^2)$.

[3]The γ-radiation level at one meter from the Godiva II core 15 minutes after a burst of 2×10^{16} fissions is $\sim$ 25 R/hour at a normal operating frequency of one burst per hour.

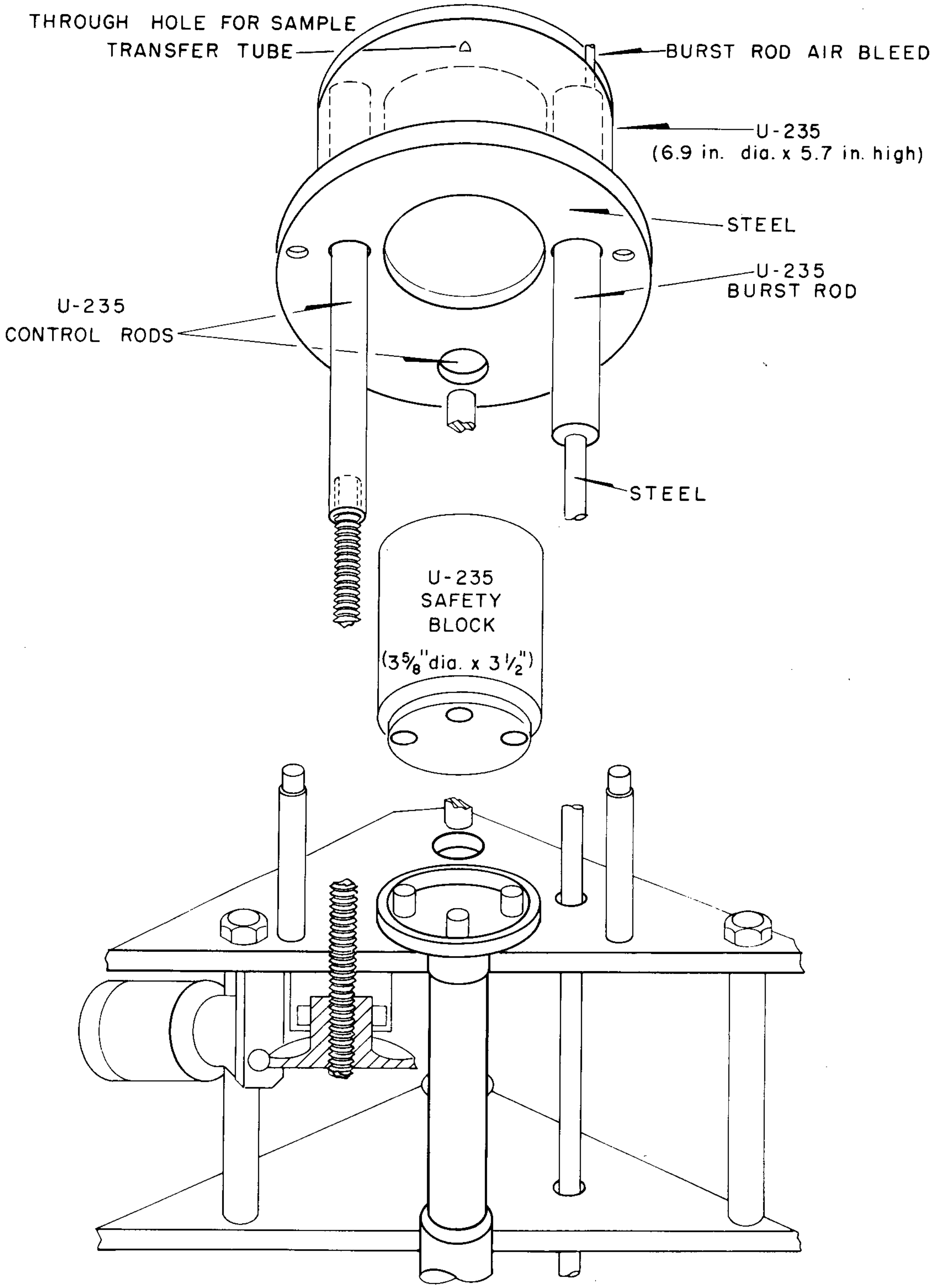

Figure 2. Drawing of Godiva II showing core detail

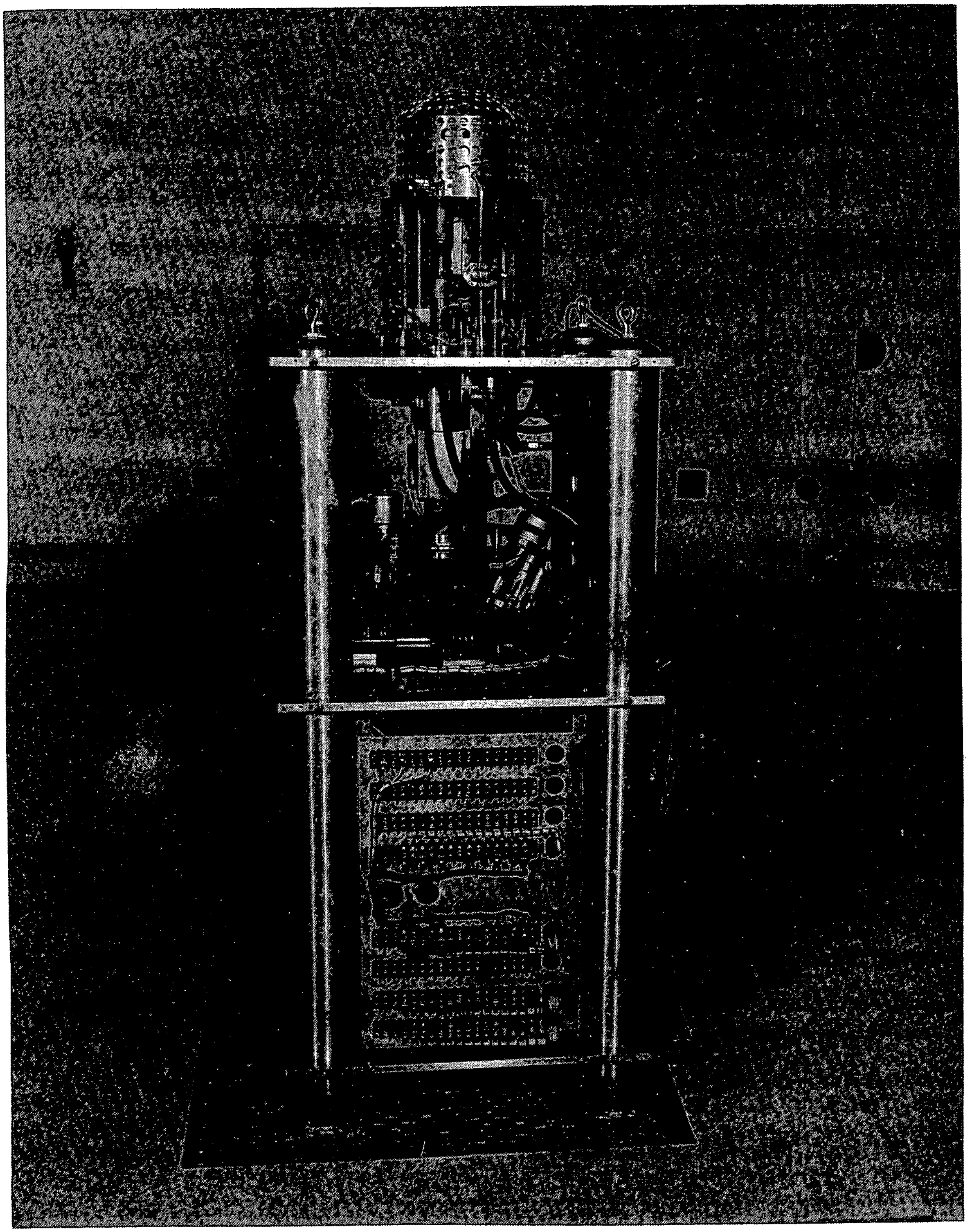

Figure 3. SPR I reactor stand with core inside protective perforated screen

In normal operation, burst reactors of the first series characteristically produce a prompt pulse in which the peak power is of order 10^4 megawatts followed by a "plateau" [7] level of order one-half megawatt. The duration of the plateau depends upon the response time of the scram system and is ~ 30 msec. Another characteristic of such reactors is the random variation in delay time, the interval between the attainment of maximum reactivity and the time of peak burst power. With no external neutron source, the mean delay time for Godiva II is ~ 3 sec [7], and is ~ 80 msec for SPR I with a Pu-Be source of 5 x 10^4 sec at a distance of 20 inches from the core. In order to reduce the undesirable plateau duration and also to provide more precise and predictable timing of the power pulse, P. D. O'Brien of Sandia Corporation has developed a technique of forced burst initiation in SPR I by which a short pulse of neutrons is introduced at the instant maximum reactivity is attained. The plateau is thereby shortened to a few milliseconds by pre-programing scram initiation, and the power pulse is predictable in time to an uncertainty of 1 - 2 μsec. The neutron source currently employed for this purpose at SPRF generates 2 x 10^8 neutrons (14 Mev) in a 10 μsec pulse and is located about 8 feet from the reactor.

Fran

The Fran design of Lawrence Radiation Laboratory represents an attempt to maximize the attainable burst yield in a pure uranium assembly. The major innovation lies in the mechanical arrangement for supporting the stationary fuel plates. In earlier designs, threshold damage produced by shock waves is usually associated with the larger components where stress buildup is greatest and tends to concentrate in the fuel support bolts. Because of fissile-metal casting limitations, a typical stationary section in a fast-burst reactor consists of several discs or annular pieces which must be clamped together in a reproducible fashion. Uranium bolts generally used for this purpose are first to yield under shock produced by the power transient in the fuel plates. In the Fran design as illustrated in Fig. 4, clamping is accomplished externally by means of two 3/4-in.-thick steel rings which overlap each end of the cylindrical stack of five annular fuel pieces, and by six 3/4-in. steel bolts that penetrate the steel rings only and are located

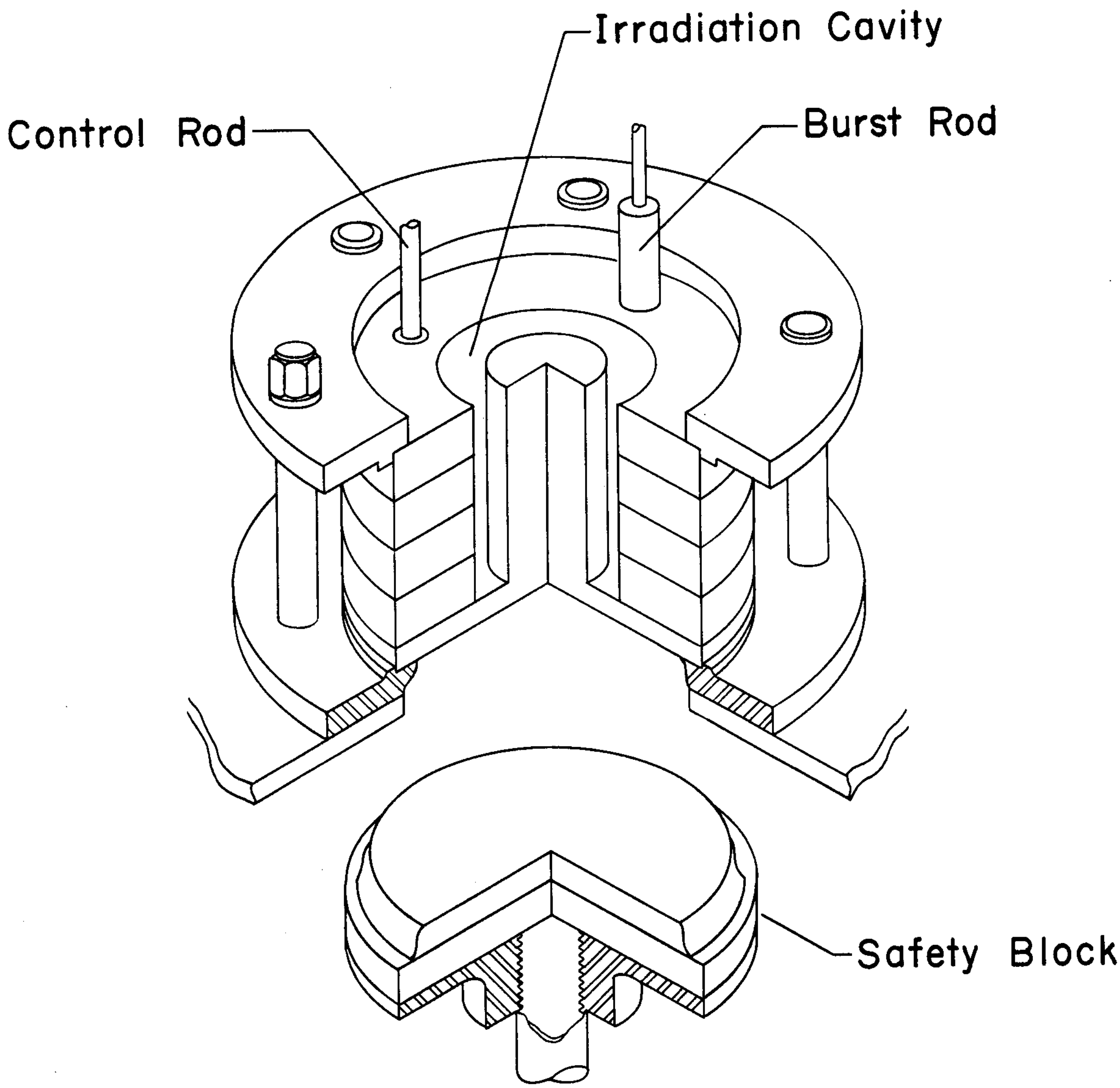

Figure 4. Isometric drawing of Fran showing core details and supports

~ 1/2 inch away from the fuel surface. In operation, the steel support plates are capable of deflecting with a large effective spring constant when the fuel expands. Burst temperature excursions approaching 350°C have been obtained on this assembly with negligible permanent deformation in either the steel supports or fuel plates. That crystal growth effects are less than observed in earlier models, may be explained on the basis of improved casting techniques which result in finer uranium grain structure.

In order to reserve the central core volume for a large annular sample irradiation void (4-in.-deep, 1/2-in.-thick, and 3 1/8-in. outside diameter), bottom fuel discs (~ 1/5 total mass) are mounted on a movable support to serve as the safety block. Control and burst rods necessarily enter the stationary section from above to avoid interference with safety block motion. Total fuel mass is ~ 63 kg.

<u>Health Physics Research Reactor, HPRR</u>

Designed and constructed by the NDA Division of United Nuclear Corporation with the support of critical experiments performed by Oak Ridge National Laboratory [8], the HPRR is the first fast-burst reactor to depart from an unalloyed uranium metal assembly. An alloy of uranium with 10 weight-percent molybdenum was selected not only for its excellent crystal-phase and chemical stability, but also because appropriate heat treatment develops higher tensile strength than uranium by a factor ~ 4 at room temperature. The reactor core, shown in the photograph of Fig. 5, is basically an 8-in.-diameter cylinder of U-10 w/o Mo alloy with a 2-in.-diameter core of stainless steel that is incorporated to reduce peaking in the core fission-power distribution. The alloy contains 90 weight-percent uranium of which 93.2% is U-235, and its total weight is ~ 115 kg. The stationary section, which is suspended from above as shown in the illustration, is ~ 9 in. high and consists of ten annular pieces of several thicknesses bolted together by 9 hollow fuel bolts 3/4 in. in diameter. The safety block is a 3.5-in.-diameter fuel annulus threaded onto a steel center plug which in turn is threaded to a smaller-diameter shaft extending upward out of the core where it is magnetically coupled to actuators. For reactivity shutdown, the safety block is thus driven out of a central cavity at the bottom of the stationary section. The usual

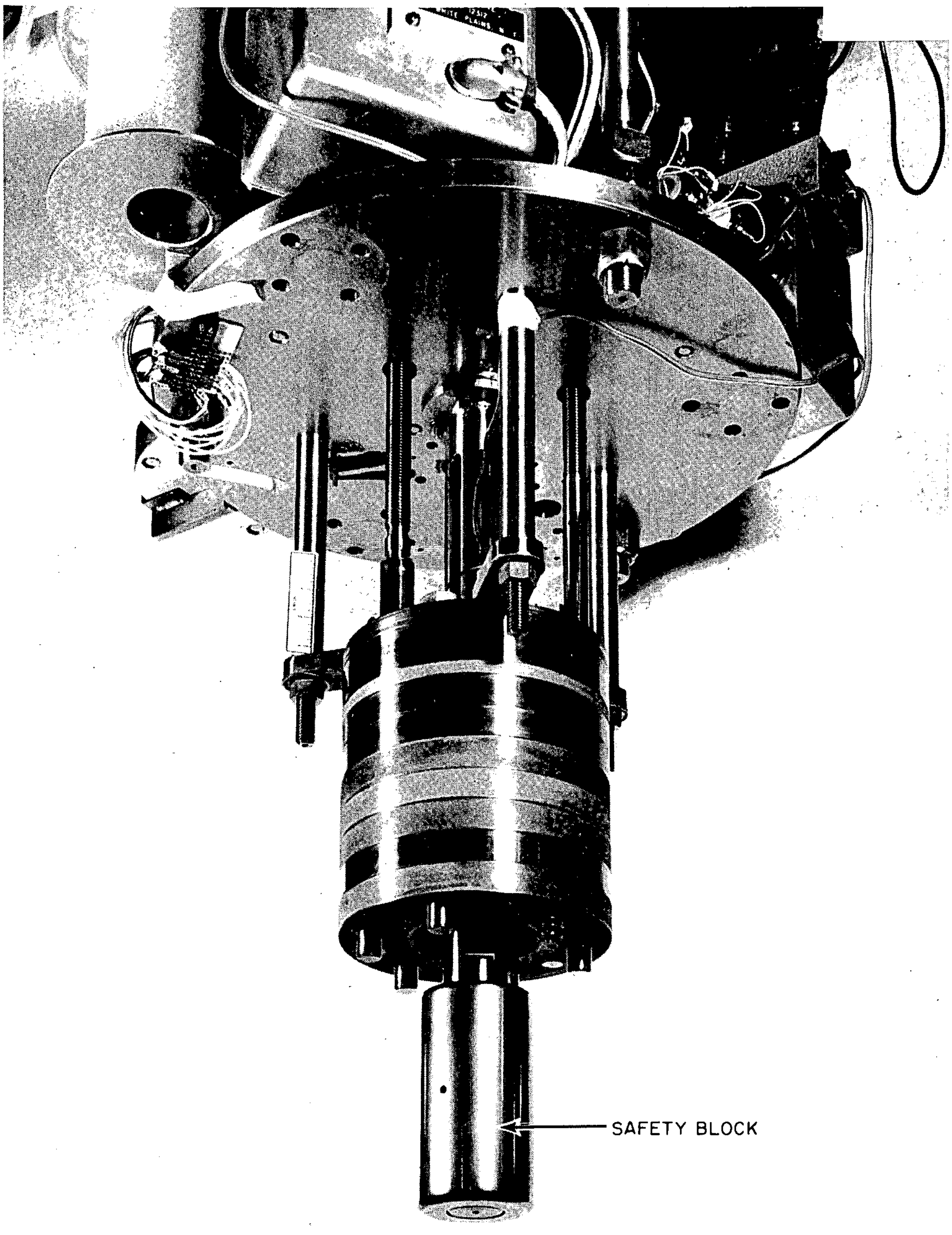

Figure 5. View of HPRR with protective tube removed to expose safety block

complement of two control rods and a burst rod are actuated from above and also enter the core from above. All exposed U-Mo surfaces are nickel plated.

Reactor portability is achieved in the HPRR system by suspending the reactor and its actuating mechanisms from a movable crane which raises the reactor from an irradiating site and transports it to a distant shielded location thus increasing residual radiation attenuation by separation distance.

In preliminary operations of HPRR, burst yields in excess of 10^{17} fissions were readily obtained with some minor shock damage observed and corrected, and it is safe to say that the maximum yield is shock-limited. However, the maximum observed temperature increases of $\sim 500^\circ C$ may be considered an upper limit for routine operation because of the onset of U-Mo phase transformation beyond $\sim 500^\circ C$.

The HPRR reactor generates "tailless" bursts or prompt power pulses which are not followed by the plateau mentioned previously. This useful phenomenon, first observed in Lady Godiva, is due to rapid displacement of the safety block as a result of mechanical shock. In the case of HPRR, a shock wave causes separation of the plate from the safety block latching magnet, and a compressed spring ejects the safety block to yield an effective scram in ~ 225 μsec.

Molly-G

The White Sands Missile Range (WSMR) Fast Burst Reactor was designed and developed by Kaman Nuclear, a subsidiary of Kaman Aircraft Corporation, with the exception of the core which was designed by WSMR engineering staff with consultation services supplied by Los Alamos Scientific Laboratory and Sandia Corporation. The core, illustrated in Fig. 6, is similar to HPRR in its cylindrical shape and use of the U-10 w/o Mo alloy. To satisfy requirements for irradiation applications, the core is mounted on a small stand similar to that of Godiva II or SPR I (thus its nickname "Molly-G" for molybdenum-alloy Godiva). The portable stand is normally fastened to a hydraulic lift which is used to lower the assembly into a pit beneath a shield (as in SPR I) inside a large reactor building, otherwise the assembly may be transported readily on a fork lift to an outdoor site for free space experiments.

The core as shown in Fig. 6 is 8 inches in diameter and 7 5/8

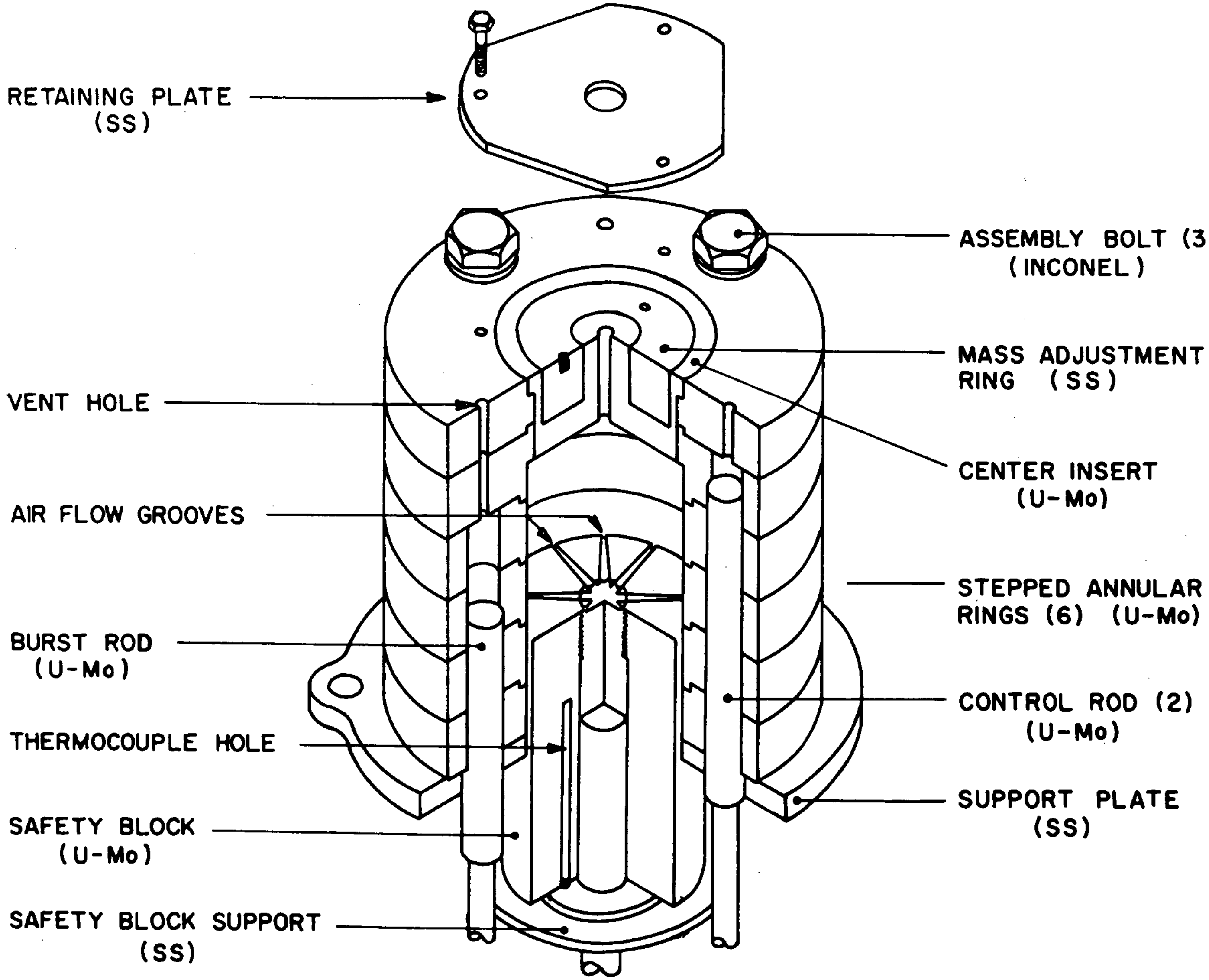

Figure 6. Molly-G core detail

inches high. The safety block is ~ 4 inches in diameter and 5 3/4 inches long with a stainless steel core 1.25 inches in diameter, and its withdrawal reduces reactivity by ~ 30$. The total weight of U-Mo is ~ 97 kg in this configuration.

Reactivity control is accomplished by the usual two control rods and a burst rod (~ 1.5$ each) and, in addition, there is provision for stepwise adjustments of ~ one dollar by means of a mass-adjustment or shim ring shown at the top of the core in the figure. For example, a shim ring of iron adds ~ one dollar while one of U-Mo adds ~ three dollars in reactivity. The fuel rings are bolted together and to the support plate by three 3/4-in. bolts. Those shown in the drawing and currently in use are made of a special high-strength nickel alloy, Inconel X, which exhibits a yield strength of ~ 180,000 psi. U-Mo bolts have also been fabricated with a predicted yield strength ~ 110,000 psi at room temperature but decreases to ~ 80,000 psi at ~ 200°C which is the predicted average bolt temperature at the instant of maximum burst stress. Experiments are in progress at WSMR to determine the bolt material best suited for the purpose.

During a preliminary series of bursts at LASL to establish limits for routine operation, the maximum burst temperature increase observed on Molly-G was 480°C in the zone of peak power density. The resultant shock experienced by the assembly (Inconel) bolts exceeded the yield point to produce a net elongation of ~ .02 inches in each bolt. Following this maximum burst and a few at somewhat lower yields, the core was disassembled for examination. Additional damage revealed was a permanent downward bowing of ~ .05 inches in the 1/2-in. stainless steel support plate, a warping of the upper retaining plate, and elongation of the smaller bolts used to attach it.

In operation at WSMR, the core has produced ~ 300 bursts of ~ 6 x 10^{16} fissions with peak temperature increases in the neighborhood of 250°C without observable damage. The shock separation of the safety block magnet produces an early effective scram very similar to that described in HPRR operation.

Super Kukla

The largest and highest-yield burst reactor of the second series or U-Mo devices is Super Kukla. The basic design [9] was developed by Lawrence Radiation Laboratory (LRL), and the assembly machine was constructed by the Baldwin-Lima-Hamilton Company with technical direction by LRL. The reactor just went into operation in December 1964, and only preliminary experimental results are available at this time. The reactor is designed to serve as a prompt burst irradiation source for a wide variety of samples which may be exposed externally or in a large internal cavity.

The core structure is illustrated in Fig. 7. Basically a cylindrical shell open at the top, it includes a cavity 18 inches in diameter and $\sim$ 24 inches high. The wall thickness is 6 inches. The height is variable and nominally 37 in. at critical with no reactivity perturbation in the cavity. The shell is composed of a stack of U-10 w/o Mo alloy rings in which the uranium is enriched to 20% U-235. The top of the cavity is reflected by means of a 6-in. tungsten disc attached to the sample container. Total fuel weight is $\sim$ 5000 kg. Large critical mass adjustments can be made by changing discs at the bottom of the lower core half. For continuous control, a gang of 6 shim rods operated individually or in combination enter the core from above and employ double-ballscrew actuators. A similar gang of rods enters from below into the lower core half and is used as a burst rod driven by a double-action hydraulic cylinder. Reactor shutdown is accomplished by dropping the lower core half which is also hydraulically actuated. Figure 8 shows the assembled reactor in the shutdown state but with the burst rod gang at its inserted position, hence protruding from the lower core half. The sample can is also visible as it hangs below the upper core half.

The maximum temperature increase observed in preliminary operations is 140°C which corresponds to a total yield of $\sim 2 \times 10^{18}$ fissions, by far the largest prompt burst yield obtained under controlled conditions. The design yield figure for this device is $\sim 5 \times 10^{18}$ fissions. No inertial shock effects have been experienced to date. Large telescoped cylindrical springs with extremely high spring constants are incorporated for vertical shock suppression in the fuel stacks.

The burst generation procedure followed in Super Kukla operations differs in two aspects from that outlined in Section 2. Firstly, in Step 1), Section 2, the delayed critical operation is

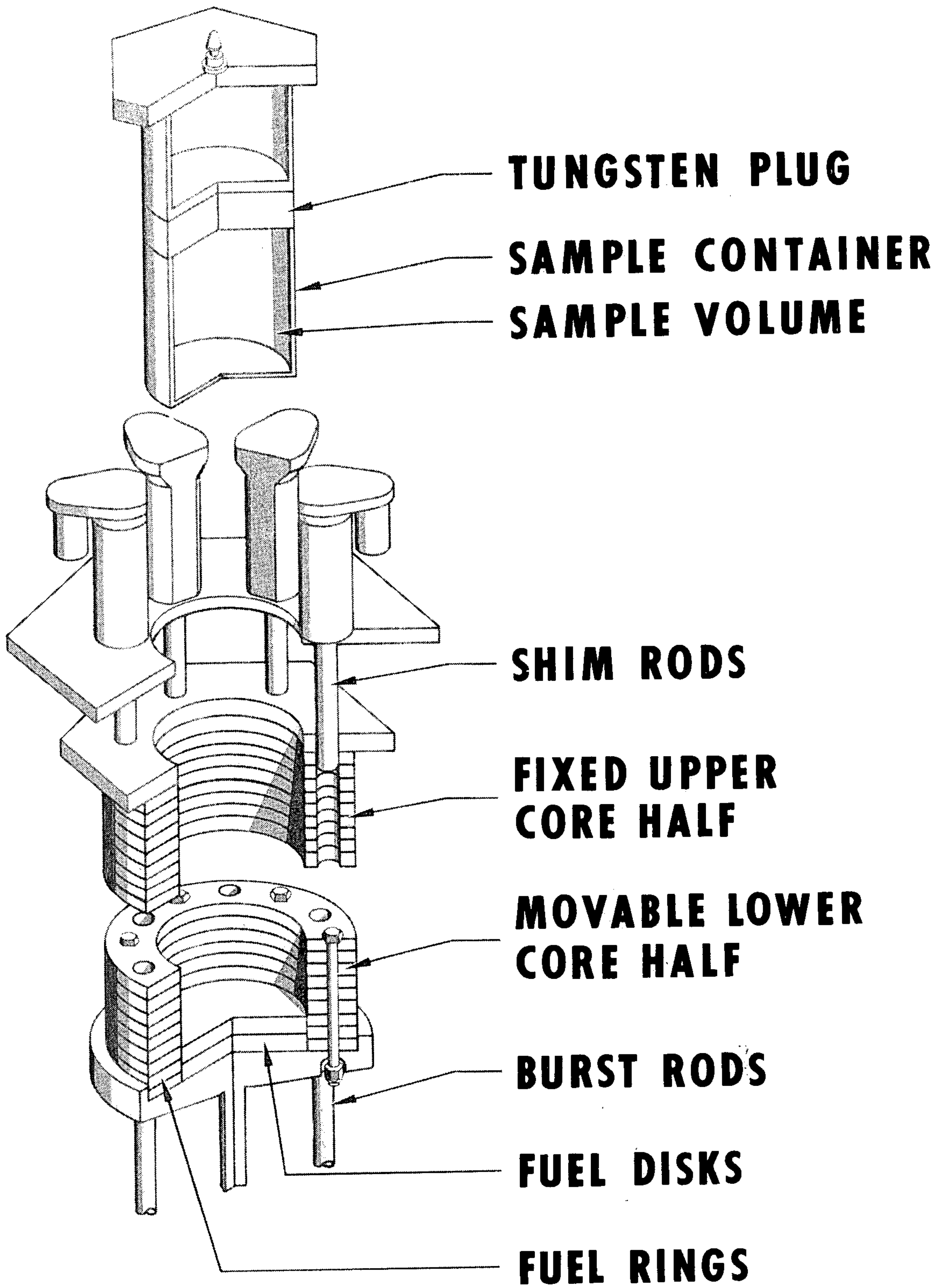

Figure 7. Exploded view of Super Kukla

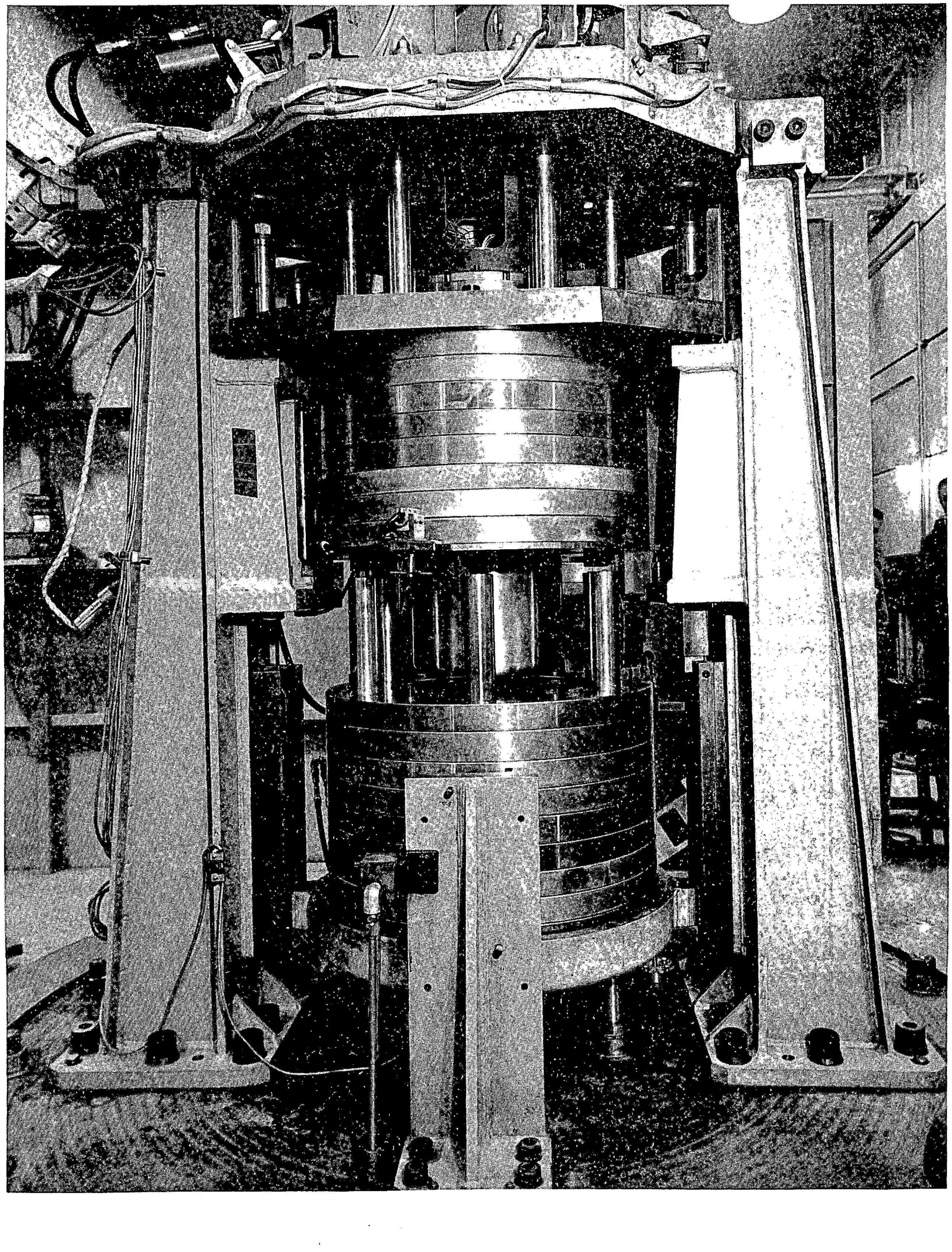

Figure 8. Super Kukla in shutdown state but with burst rods at inserted position. Sample container is visible at the center.

performed with the burst gang inserted, hence the burst gang is withdrawn in Step 2) and the shim rods adjusted so that insertion of the ~ 7$ burst rod gang leads to the desired prompt reactivity. Secondly, the neutron source remains in place during the burst mode as will be explained in Section 5.

4. REACTOR PERFORMANCE

Neutron Spectra

Neutron energy spectra for representative burst reactors may be described by the group parameters given in Table II using the six energy groups of G. E. Hansen.[10] The first line shows the fission-neutron energy spectrum for comparison purposes. The next two permit comparison between experiment and transport calculation of Godiva leakage spectra. The spectrum calculated for Molly-G is in good agreement with that for HPRR, hence typical of highly-enriched U-10 w/o Mo reactors. The Godiva data applies for all reactors of the first series discussed here. The neutron spectrum calculated for Super Kukla displays a higher contribution at lower energies owing to the low uranium enrichment and presence of massive steel components. Mean spectral energy, $\bar{E}$, shown in the table was calculated by employing group energy factors that include fission-spectrum weighting.[10]

Kinetics

The kinetic behavior of the burst reactors considered here is described adequately by means of a one-energy-group, space independent analytical model with the assumption that reactivity is a linear function of fission yield. With a first order perturbation correction for the inertial lag discussed in Section 2, analytical solutions so obtained are:

$$P = \frac{\rho_o \alpha}{2b} (1 + \alpha^2 \tau^2) \quad (1)$$

$$Y = \frac{2\rho_o}{b} (1 + \alpha^2 \tau^2) \quad . \quad (2)$$

Where P is peak burst power, Y is total prompt fission energy yield, b is a quenching constant given by reactivity change per unit fission energy released in a particular reactor, ρ_o is the initial excess prompt reactivity, α is the reciprocal stable reactor period, and τ is the inertial time constant. The full burst width measured

TABLE II

BURST REACTOR AND FISSION SPECTRA

Spectrum	0-0.1(Mev)	0.1-0.4	0.4-0.9	0.9-1.4	1.4-3	3-∞	Mean Energy $\bar{E}$ (Mev)	Comments
Fission Spectrum	.014	.090	.180	.168	.344	.204	1.95	LAMS-2543
Godiva Leakage	(.02)	.160	.274	.157	.246	.143	1.55	Experimental LA-1670
Godiva Leakage	.020	.162	.259	.160	.258	.141	1.56	DSN[a], Hansen 6 group
Godiva Central	.029	.199	.256	.150	.239	.127	1.45	DSN, Hansen 6 group
Molly-G Leakage	.023	.171	.264	.167	.246	.129	1.49	DDK[b], Hansen 6 group
Super Kukla Leakage	.045	.342	.303	.113	.127	.069	.99	DSN, Hansen 16 group
Super Kukla Central	.072	.411	.267	.093	.104	.054	.85	DSN, Hansen 16 group
Super Kukla Central (with 6" U-238 below cavity)	.100	.440	.254	.081	.083	.042	.74	DDK, Hansen 6 group

[a] DSN refers to one-dimensional neutron transport calculation [11].

[b] DDK refers to LASL two-dimensional transport calculation (S4 approximation in this case).

at half maximum power is given by $\Delta t = 3.52\ \alpha^{-1}$ for $\alpha\tau << 1$. and experimentally, $\alpha\Delta t$ decreases slowly with $\alpha\tau$ to ~ 3 as $\alpha\tau$ approaches unity. Assuming reactivity is sufficiently above prompt critical that delayed neutrons play no role, $\alpha = \rho_o \alpha_R$, where $\alpha_R \equiv \frac{\beta'}{\ell}$, $\ell \equiv$ prompt neutron lifetime, $\beta' \equiv$ effective delayed neutron fraction, ρ_o is expressed in dollars ($), Equations 1 and 2 become

$$P = \frac{\alpha^2}{2b\alpha_R} (1 + \alpha^2\tau^2) \ , \qquad (3)$$

$$Y = \frac{2\alpha}{b\alpha_R} (1 + \alpha^2\tau^2) \ , \qquad (4)$$

and, effectively, the quenching coefficient is the product $b\alpha_R$.

Observed peak burst power for the different reactors is shown plotted against burst width, Δt, in Fig. 9. The inverse square dependence on Δt for large Δt as predicted by Equation 3, with $\alpha \sim \Delta t^{-1}$, is clearly evident, and the influence of the inertial or bracketed term may be correlated with the logarithmic slope changes evident in the plots for the Godivas, Molly-G, and HPRR. The limited data for Super Kukla does not display the inertial effect owing to relatively long burst widths obtained. Noting that the quenching factor, b, varies inversely with core mass and that α_R observed for Super Kukla (see Table I) is considerably smaller than for the other reactors discussed, Equation 3 correctly predicts much higher peak powers for a given burst width in Super Kukla than for the smaller reactors. Similarly, the observed increase in burst power of HPRR over that of Molly-G as Δt approaches 50 μsec may be correlated with three factors of the expression in Equation 3. First, the mass ratio as it effects quenching constant b yields an enhancement of 1.19 for HPRR; secondly, the inverse ratio of the respective values for α_R yields the ratio 1.4; finally, the inertial factor contributes the ratio 1.56 for $\Delta t = 50$ sec (using values for τ as deduced from the data, viz., 20 μsec for HPRR and 12 μsec for Molly-G). The product of these three ratios is the predicted power ratio = 2.7 which is in fair agreement with observation.

Table III lists available neutron burst fluxes as calculated or estimated by the author from experimental or design data obtained in four different representative burst reactors. Note the gradual increase in flux integral (nvt) from Godiva at 2.5×10^{14} to $\sim 10^{15}$ in Super Kukla while the maximum flux ($nv = 2 \times 10^{19}$) is that of

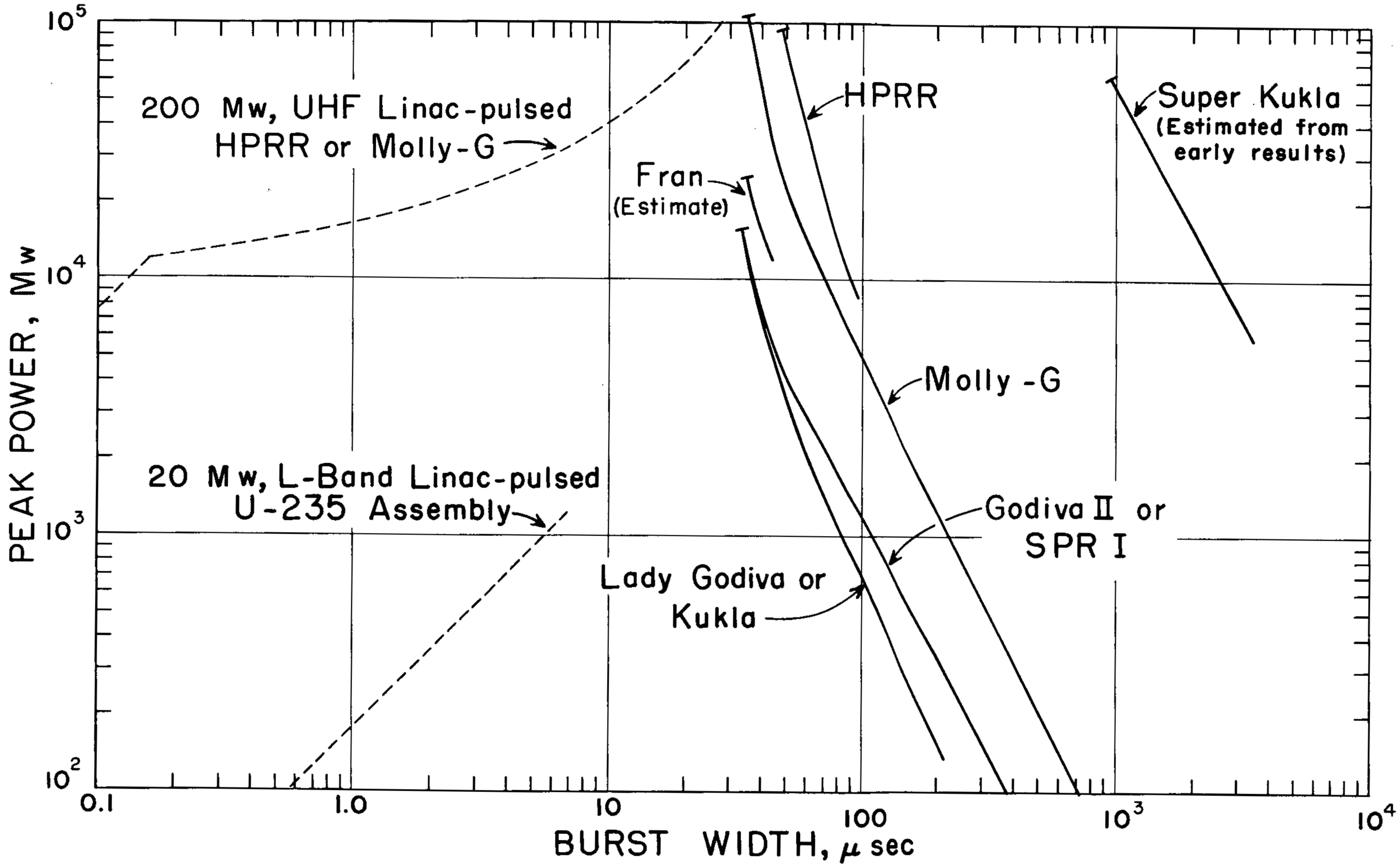

Figure 9. Burst peak power as a function of width

TABLE III

BURST NEUTRON FLUX IN TYPICAL BURST REACTORS

Reactor	Peak nv ($n/cm^2/sec$) Available External	Peak nv ($n/cm^2/sec$) Available Central	Flux integral nvt (n/cm^2) Available External	Flux integral nvt (n/cm^2) Available Central
Godiva II, or SPR I	3×10^{17}	4×10^{18}	1.5×10^{13}	2×10^{14}
Fran	6×10^{17}	1×10^{19}	2×10^{13}	3×10^{14}
Molly-G	1.5×10^{18}	2×10^{19}	5×10^{13}	7×10^{14}
Super Kukla (from design figures)	3×10^{17}	4×10^{18}	1.5×10^{14}	2×10^{15}
Super Kukla (from early experimental data)	6×10^{16}	9×10^{17}	6×10^{13}	8×10^{14}

Molly-G. This is, of course, a result of considerably shorter burst widths in Molly-G than in the high-yield Super Kukla which in turn result from the difference in neutron lifetimes ($\ell \sim 6 \times 10^{-9}$ sec in Molly-G and $\sim 1.5 \times 10^{-7}$ sec in Super Kukla). The flux integral available in the cavity of Super Kukla is sufficient to melt fissile samples and exhibits a nearly-flat spacial distribution as shown by the calculated curves of Fig. 10. The upper curve shows the radial flux distribution near the central region and includes the maximum cavity flux. The lower curve shows the minimum cavity flux which occurs near the tungsten plug at the top of the cavity. These results were obtained by two-dimensional transport calculation (DDK) at LASL and apply to a particular core geometry, e.g., with 6 inches of U-238 at the bottom of the cavity.

In order to estimate the yield of thermal neutrons per burst with different amounts of neutron moderation, calculations were performed on a spherical reactor (Godiva) surrounded by plastic (Lucite) moderators of different thicknesses. Between the moderator and reactor was placed a 1/2-in. layer of heavily-loaded boral to minimize burst broadening due to coupling between reactor and moderator. The calculations were performed using the LASL one-dimensional transport code, DTK, with sixteen energy groups.[10] Results in the form of differential leakage parameters for energy groups up to 10^5 ev are shown in Fig. 11. By extrapolation on the basis of total burst fissions, a total predicted thermal flux for Molly-G is indicated on the curves. Thus for a burst of 10^{17} fissions, a total thermal flux of 2.2×10^{12} n/cm^2 is available from a 2-inch moderator. Assuming the pulse is lengthened by die-away time to $\Delta t = 100$ μsec, this corresponds to a peak thermal flux, $nv = 2.2 \times 10^{16}$ n/cm^2/sec.

5. REACTOR SAFETY

Because of low repetition rates, time-averaged operating power levels for fast burst reactors are generally less than a kilowatt. This means that the radioactive fission fragment inventory is small and its dispersal as a result of an explosive accident generally would not be a matter of public-safety concern. Questions of more legitimate concern are those associated with possible low-level disruptive damage which may accompany the stepwise assembly necessary

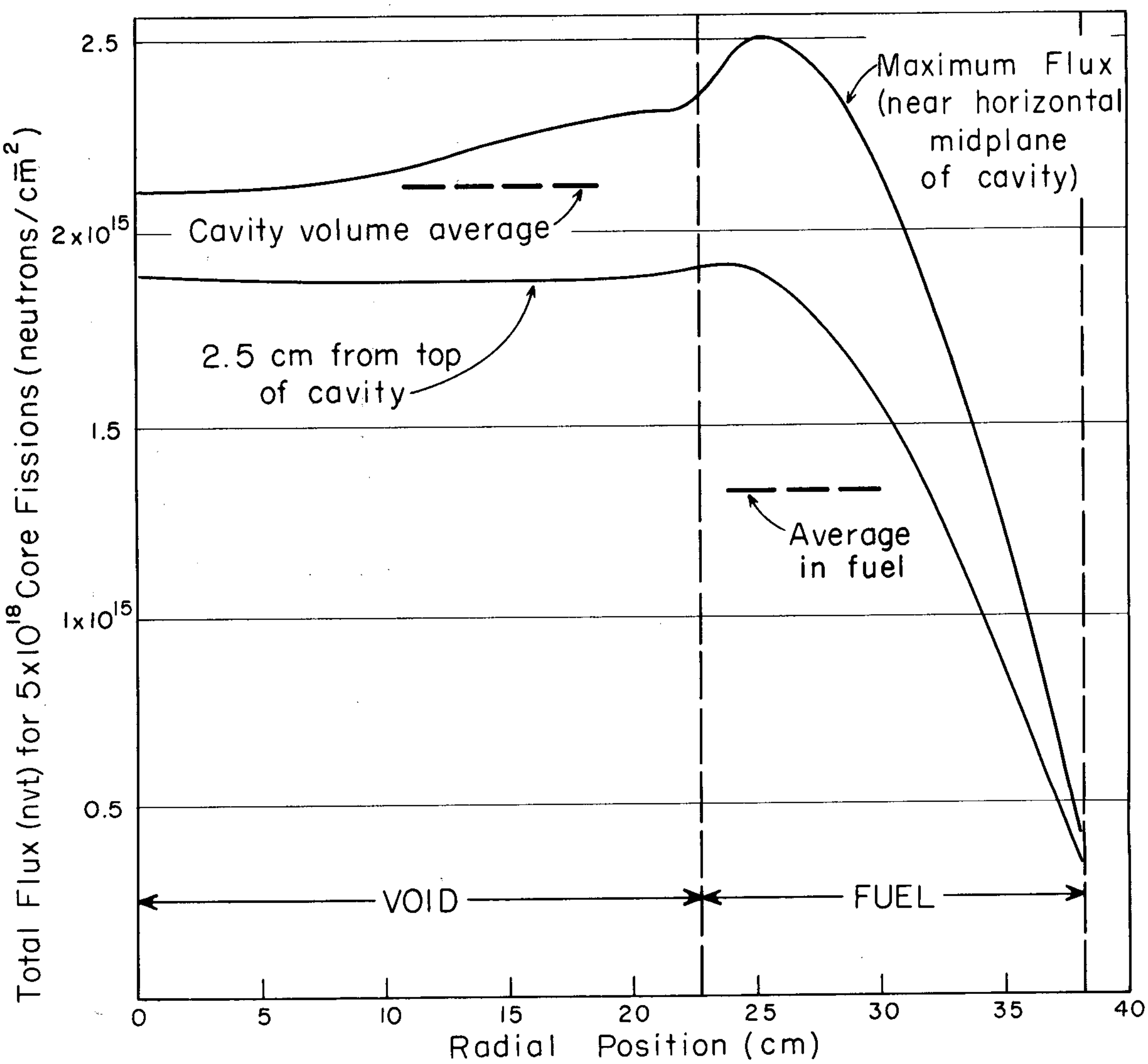

Figure 10. Total flux as a function of radius in Super Kukla

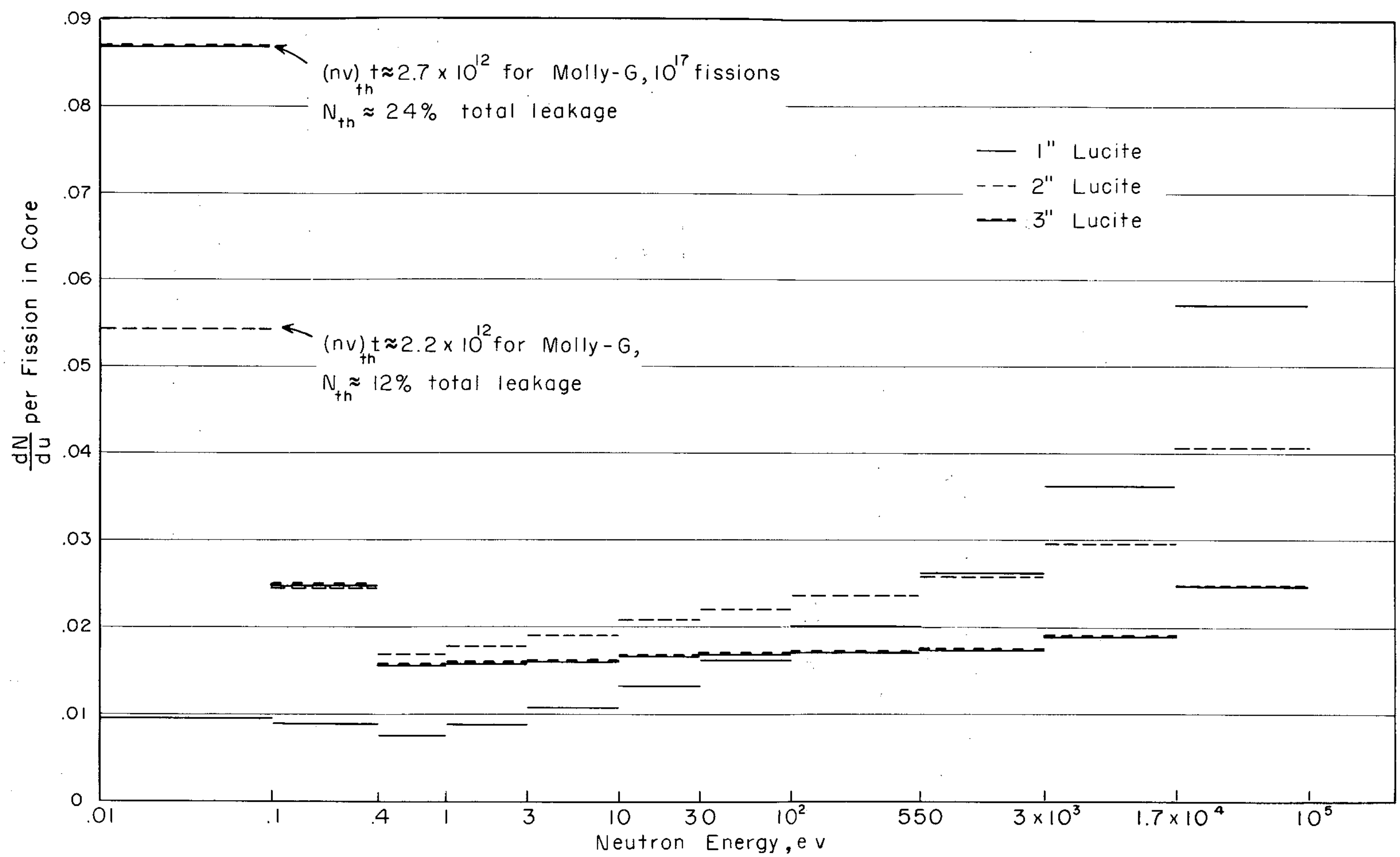

Figure 11. Leakage neutron energy distribution computed for different thicknesses of Lucite surrounding Godiva-like burst reactor. Ordinate is neutron fraction (dN) per core per lethargy interval with an interval of 2.3 chosen for the thermal group.

for prompt burst production. Protection of operating personnel from direct radiation is provided by remote operation from a distant or well-shielded control room.

In burst reactor operation, two occasions arise in which an unexpected power excursion may occur as a result of inadvertent reactivity additions introduced, for example, by neutron reflectors near the bare core. The first occasion is the initial approach to critical, or Step 1, Section 2, and the second is when the safety block and burst rod are inserted at Step 3. A specified slow rate of reactivity addition, coupled with the presence of a suitable neutron source, provide the customary safeguard in Step 1. During Step 3, when at most a weak neutron source is present, safety resides chiefly in careful operational control so as to avoid accidental reactivity changes after the delayed-critical check. Furthermore, the accidental addition of more than a half-dollar excess reactivity between Steps 2 and 3 will normally be discovered either by means of constant reactor surveillance or by a detectable increase in power level before burst rod insertion. A small possibility remains, however, of an oversized burst caused by the accidental addition of up to one-half dollar at this point. That possibility is normally considered to define the maximum credible accident that serves as a basis for judging the need for containment or confinement.

For most fast burst reactors, there is a basic incompatibility between absolute safeguards against unplanned prompt excursions and the reproducible generation of prompt bursts. A sufficiently large neutron source will lead to a buildup in neutron population and initiate reactivity quenching by fission energy release, hence prevent an accidental prompt excursion at the available reactivity insertion rate. But the same source, by preinitiation, may prevent attainment of the superprompt state necessary for an intentional burst. The problem of predicting energy release under ramp conditions has been considered by G. E. Hansen [12] who shows that the probability that the neutron population remains below a specified level at a particular reactivity depends primarily upon the time fluctuation in establishment of a persistent neutron chain and secondarily on the time fluctuation in growth of a chain. G. I. Bell et al. [13] have developed a machine code which approximates this probability in terms of a probability-distribution generating function. Solutions obtained by the (Bell) code for cases of interest are shown in Fig. 12 where the probability that the neutron population remains less than an arbitrary 10^5 neutrons at the reactivity is plotted versus ρ_p for different ramp rates and neutron source strengths. The upper curve is representative of burst rod reactivity insertion without external source for many of the small burst reactors. The spontaneous fission source strength, S_o, in Godiva II is ~ 100 n/sec but is often increased to 300 n/sec by multiplication after safety block insertion and before burst rod insertion, while the natural source for Molly-G and HPRR is about twice that of Godiva II. The burst reactivity insertion rate currently used on Super Kukla is ~ 40 \$/sec and the natural source is ~ 6×10^4 n/sec. The appropriate probability function is as shown in the Figure. Clearly, there is finite probability of reaching $\rho_p = 0.5\$$ with no excursion taking place in operation of Godiva II and Super Kukla without external source if the ramp (inadvertently) reaches such reactivity. By increasing the sources to values as shown on the lower curves, the probability of exceeding $\rho_p = 0.5\$$ without burst initiation may be reduced to a negligible level for either device.

In order to examine the problem of burst preinitiation, we determine the probability that the neutron population at ρ_p will be equal to or greater than that corresponding to a full amplitude burst. Functions so-obtained are presented in Fig. 13. From the upper curve, it is apparent that a neutron source of 2×10^5 n/sec for Godiva which provides protection against excessive bursts as shown in Fig. 12 results in a 35% preinitiation probability at the maximum operating reactivity, $\rho_p = 0.1\$$. For Super Kukla, on the other hand, the "safe" source of 3×10^5 permits operation with negligible preinitiation probability up to $\rho_p = 0.2\$$ which is very near the design-maximum operating point.

6. PRESENT STATUS AND FUTURE PLANS

The limit of peak power in self-quenching bursts is presently ~ 10^4 Mw as obtained in Molly-G. The maximum yield is ~ 60 megajoules in the 5000-kg Super Kukla. The shortest burst width obtained is ~ 35 μsec as observed in the smaller reactors having short neutron lifetimes.

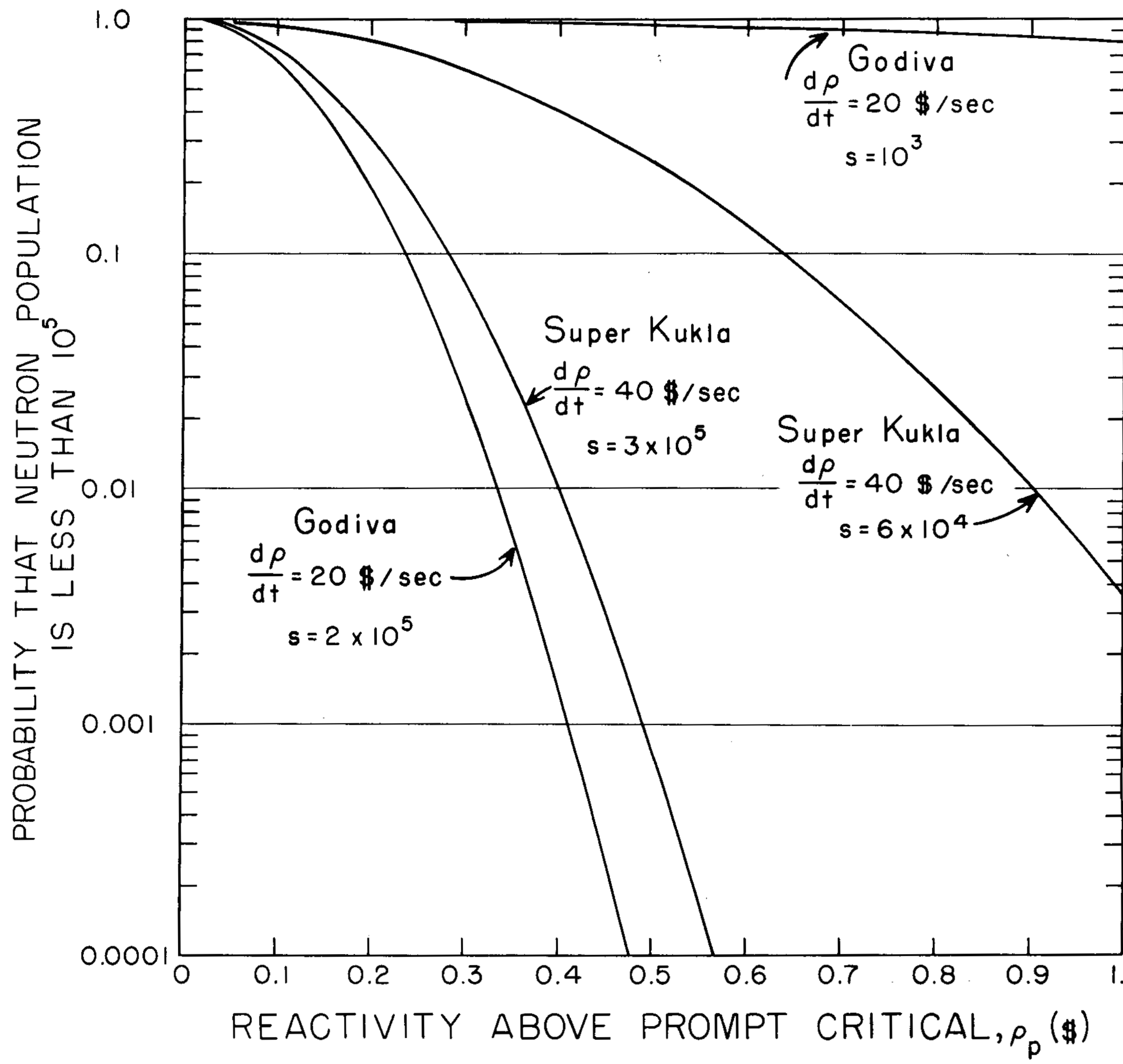

Figure 12. Probability that core neutron population is below 10^5 neutrons for different reactivity insertion rates

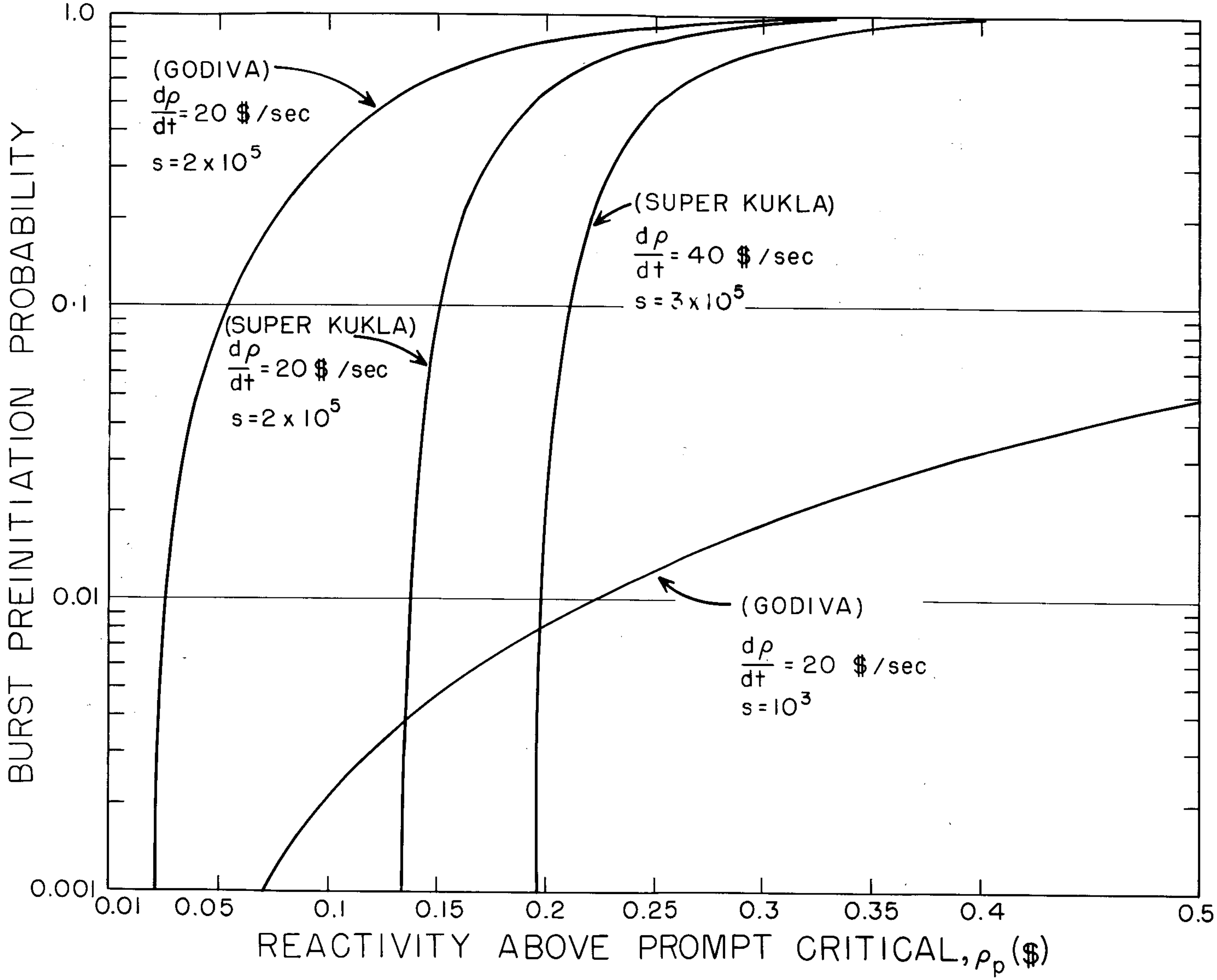

Figure 13. Burst preinitiation probability for different reactivity insertion rates

For high intensity bursts less than 35 μsec in width, J. R. Beyster [14] and others at General Atomic have been investigating the bombardment of a super-critical fast reactor with the electron beam of a high current linear accelerator (Linac). They have obtained bursts up to 300 Mw with half widths ~ 3 μsec by pulsing a bare U-235 supercritical reactor with a 20 Mw L-band Linac. Because core requirements are very similar to those for short-burst generation in a self-quenching burst reactor, viz., short neutron lifetime and a shock-resistant core structure, the small U-Mo reactors discussed here are optimum choices for bombardment. The upper dashed curve in Fig. 9 shows performance predicted for the pulsing of a Molly-G type reactor using a proposed 200 Mw Linac. The lower curve shows predicted operation with currently available equipment. These results are taken from Reference [14].

To further extend the range of operation of bursts from fast reactors as illustrated in Fig. 9, high-strength fuel alloys are being examined at LASL. A new scheme of burst generation is being developed at Sandia Corporation for use on a U-Mo reactor in which a burst is pulse-initiated the instant a fly-through burst rod attains maximum reactivity. This is expected to result in more reproducible "tailless" bursts. A new shock-resistant core concept shown in Fig. 14 is being developed at LASL which includes center of mass support and spring clamping.

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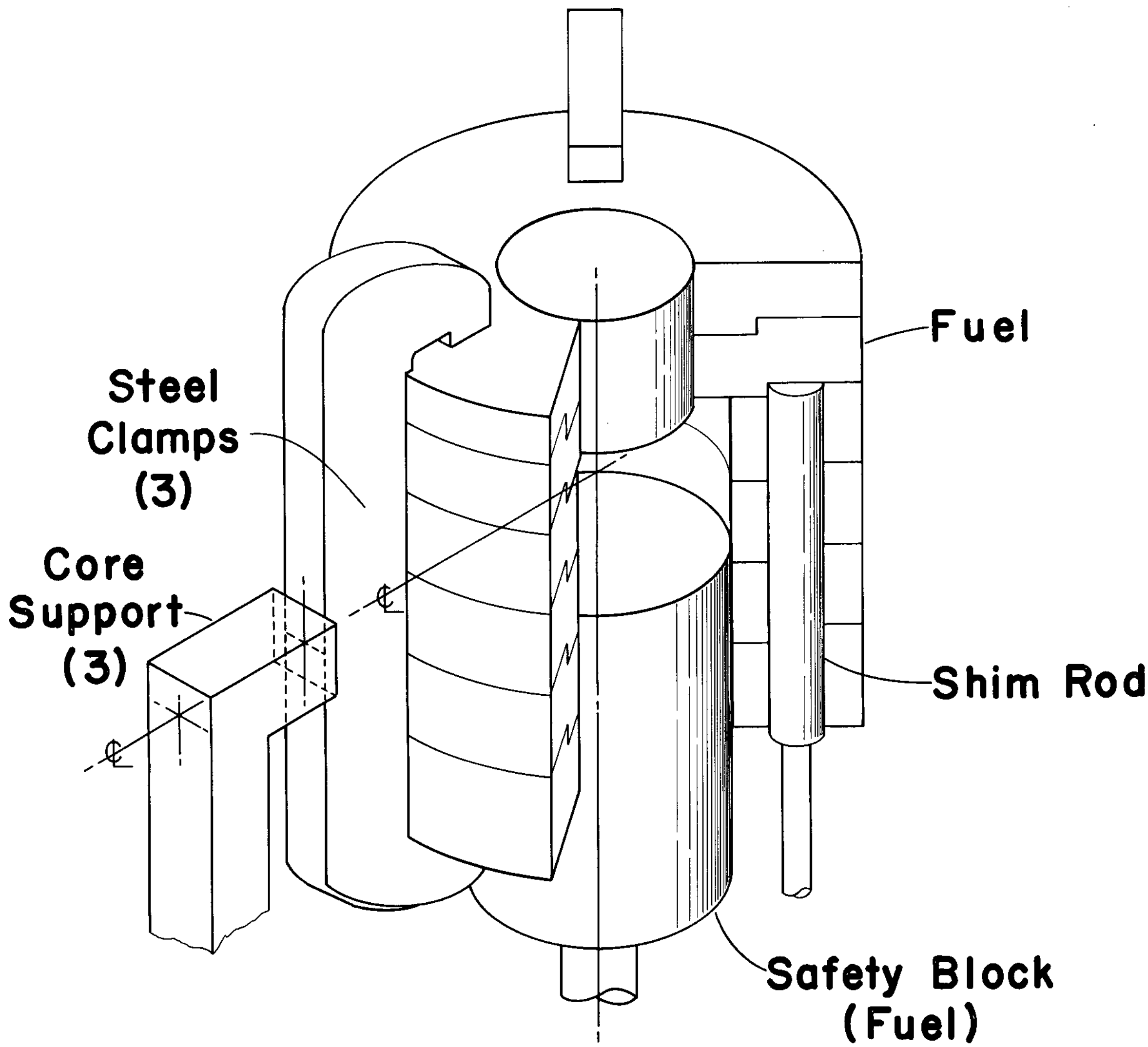

Figure 14. New LASL reactor design concept for shock suppression

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