**Safety Analysis Report for the
Hanford Critical Mass Laboratory:
Supplement No. 2—Experiments
with Heterogeneous Assemblies**

**B. F. Gore
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April 1981

**Prepared for the U.S. Department of Energy
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SAFETY ANALYSIS REPORT
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EXPERIMENTS WITH HETEROGENEOUS ASSEMBLIES

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SUMMARY

Factors affecting the safety of criticality experiments using heterogeneous assemblies are described and assessed. It is concluded that there is no substantial change in safety from experiments already being routinely performed at the Critical Mass Laboratory (CML), and that laboratory and personnel safety are adequately provided by the combination of engineered and administrative safety limits enforced at the CML. This conclusion is based on the analysis of operational controls, potential hazards, and the consequences of accidents. Contingencies considered that could affect nuclear criticality include manual changes in fuel loadings, water flooding, fire, explosion, loss of services, earthquake, windstorm, and flood. Other potential hazards considered include radiation exposure to personnel, and potential releases within the Assembly Room and outside to the environment.

It is concluded that the Maximum Credible Nuclear Burst of 3×10^{18} fissions (which served as the design basis for the CML) is valid for heterogeneous assemblies as well as homogeneous assemblies. This is based upon examination of the results of reactor destructive tests and the results of the SL-1 reactor destructive accident. The production of blast effects which might jeopardize the CML critical assembly room (of thick reinforced concrete) is not considered credible due to the extreme circumstances required to produce blast effects in reactor destructive tests. Consequently, it is concluded that, for experiments with heterogeneous assemblies, the consequences of the Maximum Credible Burst are unchanged from those previously estimated for experiments with homogeneous systems.

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INTRODUCTION

Research programs at the Critical Mass Laboratory (CML) require measurements using heterogeneous critical assemblies of fissionable material. Data obtained are commonly used in the validation of computational models for reactor core physics, and in the evaluation of criticality safety during fuel cycle operations which include storage, transport, reprocessing, and refabrication. Due to the nature of heterogeneous assemblies and the form of the fuel there are some minor differences in procedural requirements for these systems compared to systems that were analyzed previously for the Critical Mass Laboratory. For instance, heterogeneous critical assemblies are constructed by manually loading fissile material into lattice templates or other positioning devices. In homogeneous experiments, solutions are added remotely and, for experiments using solid compacts of fissile material and moderator, the remotely operated split table machine is used. Nevertheless, all experimental assemblies are equipped with safety devices, activated both automatically and manually, capable of rendering the assemblies subcritical and maintaining them in that condition.

This report describes the types of experiments and equipment, presents the operating limitations that minimize the probability for occurrence of a nuclear accident in heterogeneous assemblies of fissionable material, and discusses the potential types and consequences of accidents which might occur.

NUCLEAR SAFETY LIMIT

This limit is specified in BNWL-MA-86, Technical Specifications for the Critical Mass Laboratory.¹

- The experimental assembly shall not achieve prompt criticality.

The CML is not designed for experiments on prompt critical systems, so they are not allowed. The objective of this limit is to preclude conditions which could result in significant release of fissionable material or fission products inside the assembly room.

In this document only the Nuclear Safety Limit is regarded as binding. Other limits, discussed in the following section, support this limit. They may be revised (with appropriate review and approval) if it can be demonstrated that the revisions do not compromise the safety of CML operations. However, any change in the equipment or operations of the CML which could result in a significant change in the nuclear safety of the facility will require an additional supplement to the SAR.

OTHER LIMITS

The Nuclear Safety Limit is supported by other limits on safety circuit settings and conditions for operation published in the Technical Specifications. The purpose of the supporting limits is to assure that adequate information about the state of the assembly is available so that off standard conditions are promptly recognized and responded to, and that adequate shutdown capability is available. Additional limits address monitoring and alarm systems, the assembly room containment system, fuel storage and handling, and surveillance and testing of assembly room systems.

Some examples of current Technical Specifications which apply to operation with heterogeneous assemblies are listed below to indicate the content of the Specifications.

- The experimental assembly period safety circuit trip setting shall not be less than 10 seconds.
- The maximum excess reactivity¹ shall be limited to \$0.75.
- The shutdown margin¹ shall be at least \$2.
- Each experimental assembly shall have at least two independent safety devices, either of which shall be capable of rendering the assembly subcritical within 1.0 seconds (including safety circuit delay).
- There shall be at least two independent and operable safety channels in service monitoring the reactor flux level. One of these shall be a linear channel.
- Loss of actuating power to any safety device shall cause that device to scram to the position for which the assembly is least reactive.
- Interlocks and controls shall be in place to assure that instrumentation, equipment and devices specified in these technical specifications shall be operable as required.

In addition to this incomplete list of limiting conditions for operation, the Technical Specifications also address surveillance requirements, engineered design features of the facility, and administrative controls.

These Technical Specifications may be revised if it can be demonstrated that the revisions do not compromise the safety of CML operations. Such changes require approval of the Manager of DOE-RL in addition to internal PNL approval. It is important to the continued operation of the CML that revisions to the Technical Specifications are possible as experimental needs change with time. Prior to experimentation with heterogeneous systems access to the critical assembly room was forbidden when an assembly contained 90% or more of the assembled critical mass. This was practical since solution additions were made remotely and, for experiments using the remotely operated split-table machine (RSTM), separation of the table halves reduced assembly reactivity to meet this criterion. To allow the safe assembly of critical heterogeneous assemblies the Technical Specifications have been revised² to include:

- No manual reactivity additions shall be made to any assembly containing more than 90% of the critical mass for the assembly unless multiplication data for the experiment in progress show that with such additions the assembly shall remain subcritical.
- The quantity of material added to an experimental assembly containing more than 90% of the critical mass for the assembly, shall be less than 85% of the increment predicted to achieve criticality with the control device(s) in that position for which the experimental assembly is in its least reactive condition.
- Manual pouring of fissile material solutions into an experimental assembly is prohibited.

- Access to the assembly room for other than operations on the experimental assemblies shall be permitted only when the assembly is in a deactivated condition or with the approval of the senior experimenter in charge of the experiments in progress, wherein such entry will not affect the safe conduct of the experiment.

The purpose of the first two of these added operating limits is to restrict the quantity of fuel which can be loaded at each step to preclude accidentally loading an assembly to criticality. During fuel loading the subcriticality of a heterogeneous assembly is maintained by a control blade. A safety blade is also poised for insertion should further reactivity reduction be needed (see the discussion of Section - Experimental Assembly and Control Blades). In addition, CML instrumentation is operated to detect and automatically respond to any indication of off-normal conditions (see Section - Instrumentation). The flux level and rate of change in the assembly are continuously monitored, and a system of interlocking relays acts to automatically reduce assembly reactivity by inserting the safety blade if preset limits are exceeded (see Section - Safety and Interlock System).

Formalized procedures are used to determine the amount of fuel to be loaded in each increment so that the limits specified above are not exceeded. Agreement between the independent calculations of two qualified people is required before fuel is loaded (see Section - Analysis of System Hazards). It is concluded in Section - Analysis of System Hazards that with these limits, procedures, instrumentation and safety systems, the manual loading of heterogeneous critical assemblies results in no degradation of safety from that achieved during the manual loading of critical assemblies on the split table.

The purpose of the added limit precluding manual pouring of fissile solutions is simply to ensure that present practice for the addition of fissile solution to experimental assemblies is continued.

The purpose of the fourth added operating limit is to restrict assembly room entry when an experimental assembly contains more than 90% of a critical mass or when remote means of increasing reactivity beyond 90% of a critical mass are present (i. e. when the assembly has been advanced from the deactivated, shut down mode to the operational mode). Assembly room entry is required for a variety of reasons not directly related to experimentation. Included are needs for security checks, audits, radiation monitoring, housekeeping, equipment maintenance and modification, and installation of equipment. Because reduction of the fraction of a critical mass contained in a heterogeneous assembly requires the manual removal of fuel, which is undesirable from the standpoints of operating efficiency and radiation exposure, provision has been made to allow assembly room entry when a heterogeneous assembly is in the operational mode if it will not reduce the safety of experimentation. Responsibility for determining whether assembly room entry is permissible is assigned to the senior experimenter in charge. However, when an experimental assembly is in the normal operational mode, and entry is permitted for purposes other than reactivity modifications to the assembly, no modifications may be made that would advance the assembly nearer to criticality.

To ensure that the conduct of operations at the CML remains within the limits of the Technical Specifications, additional rules for operation have been formulated and are published in BNWL-MA-60, Critical Mass Laboratory Operating Specifications.³ These rules define conservative operating limitations, safety circuit and device requirements, administrative control requirements, auxiliary system performance, and fuel storage and transfer limitations to keep operations within the limits specified in the Technical Specifications. The Operating Specifications may be revised if it can be demonstrated that the revision does not compromise safety at the CML. Revision of the Operating Specifications requires review and concurrence by PNL's Technical Leader, Nuclear Safety and Manager of the Energy Systems Department.

Some examples of current Operating Specifications which apply to operation with heterogeneous assemblies are listed below to indicate the content of the Specifications.

- Each critical assembly shall be provided with two or more independent systems, any one of which by itself is capable of shutting down and maintaining the assembly in a shutdown condition in any foreseeable conditions.
- Each safety system shall render the assembly subcritical within 1.0 second (including safety circuit delay).
- Loss of actuating power to a safety device shall cause it to assume the configuration for which the critical assembly is least reactive.
- The combined functioning of all safety devices shall leave the assembly at least 4.00×10^{-4} subcritical.
- The maximum excess reactivity in an assembly shall not exceed 0.75×10^{-4} with all safety and control devices in their most reactive configuration.
- The proper functioning of the safety devices shall be established each operating day prior to starting operations.

As has been discussed, revisions have been made to the Technical Specifications and the Operating Specifications to accommodate experimentation with heterogeneous assemblies. It is expected that planned work can be accomplished within these limits. However, the possibility exists that, following appropriate safety review, additional revisions may be made to accommodate future activities which can be demonstrated not to compromise safety at the CML.

Fissionable material outside of critical experiment assemblies is handled, transported, or stored in accordance with Criticality Safety Procedures, PNL-MA-25.⁴ These procedures governing the handling, transporting, and storing of fissionable material are based upon the double-contingency criterion, which requires that at least two unlikely, independent, and concurrent changes in process conditions occur before a nuclear incident is possible.

SITE AND FACILITY DESCRIPTION

The CML, shown in Figure 1, is located in the central part of the 200 East Area of the Hanford reservation. The site is arid and sparsely populated. Additional description of the site is given in the original Hazards Summary Report for the Hanford Plutonium Critical Mass Laboratory, HW-66266.⁵ A much more complete and up-to-date general site description is also available in Final Environmental Statement, Hanford Waste Management Operations, ERDA-1538.⁶

An extensive description of the facility is given in the original Hazards Summary Report for the Hanford Plutonium Critical Mass Laboratory, HW-66266⁵ and its Supplement No. 1, The Remote Split-Table Machine, HW-66266, Supplement 1 - Revised.⁷ The description of the critical assembly room, in which all critical assemblies are constructed, is reproduced below. The features of structural strength, radiation shielding and radioactivity containment which make this assembly room unique are described.

"The assembly room within which the critical experiments are to be operated has internal dimensions of 35 x 35 feet and a ceiling height sloping from 20 to 21 feet. It is made entirely of ordinary concrete containing reinforcing steel bars. Conventional design and construction practices were used. The walls on three sides (facing the rest of the present facility and the area of future expansion) are five feet thick. The fourth wall is three feet thick and the floor and ceiling are each two feet thick. This structure provides both shielding for normal and abnormal radiation levels within the cell and also the structural strength to withstand internal pressures potentially present in the event of a nuclear burst. The design pressure is 4.5 psig. The acceptance tests of the room have shown that the leak rate at 4.5 psig is 0.42 to 0.5 volume percent per hour. [The current technical specifications require annual testing to demonstrate a leak rate no more than 0.5

Figure 1. Plutonium Critical Mass Laboratory

volume percent per hour at an overpressure of 2.0 psig. The testing pressure has been reduced to minimize 'working' and fatiguing of the building joints which could increase leakage.]

All the interior surfaces of the concrete, including the floor, are coated with a fiber glass reinforced resin surface (Amercoat No. 74). This coating provides a hard impervious surface which may be easily decontaminated and in addition, forms a gas tight seal over hair-line cracks and crazing in the concrete.

All pipes and conduits which penetrate the reactor-assembly room are welded to steel plates set flush with the interior surface of the concrete; the coating extends over the plate to minimize leaks from the room along the pipes at these points.

There are two entrances to the room. A labyrinth passage provides a shielded personnel entrance from the rest of the facility. At the inner end a gasketed steel door serves for gas tight containment, while a regular door at the outer end serves to keep the passage closed off during operation. A large concrete and steel door in the south wall provides access for large equipment. This door provides a clear opening about 9 x 9 1/2 feet (large enough to pass the containment hoods within which the assemblies are set up). The door itself is constructed of plate steel and is filled with concrete. The total thickness is 2 1/2 feet. The whole door swings on a single, roller-bearing mounted, hinge post and is operated by an electric drive. When closed, the door is sealed by means of two inflatable gaskets between the door and the frame. The effectiveness of the seal may be checked at any time by pressurizing the space between the two seals; leaks are then observed by noting pressure losses.

Two openings are provided for ventilation, an inlet and an exhaust. These are both 12 inches in diameter and are equipped with motor driven butterfly valves having resilient rubber seats for gas tight seal at the design pressure.

A heating and air conditioning unit is hung from the ceiling of the room. This unit recirculates the air in the room, and is self-contained except for steam and chilled water supplied from outside the room. The outside air inlet to the room opens into the inlet plenum of the air conditioning unit, but air enters the room only by virtue of the slight negative pressure induced by the air withdrawal at the room exhaust.

Air entering the unit is filtered by an initial glass fiber filter followed by an additional [HEPA] filter. Air leaving the room also passes through a [HEPA] filter before entering the exhaust system. The [HEPA] filters are the high efficiency-fire-resistant type recommended for air cleaning at [DOE] installations. Stated efficiency is 99.95 per cent for 0.3 micron particles. "Fire resistant" means that the filter, particularly the filter media itself, is noncombustible (will not support combustion) although parts such as the frame and adhesive may be consumed if subjected to sufficient heat.

The exhaust and inlet valves are operable from the control room. The exhaust valve, however, is interlocked so that it may not be closed until all other openings are closed. Conversely, if the room is sealed, opening any door or the inlet valve will cause the exhaust valve to open immediately. This pattern serves to minimize the escape of any air-borne contamination in the room except through the filtered exhaust system."

EXPERIMENTAL ASSEMBLY AND CONTROL BLADES

The fuel for heterogeneous assembly experiments will contain one or more of the fissile isotopes ^{233}U , ^{235}U , and ^{239}Pu - ^{241}Pu ; plus the fertile isotopes Th and ^{238}U . Permissible forms for solid fuels are powders, compacted powders sintered pellets, metals, and alloys. Powder fuels will be contained so that geometrical configuration is maintained and contamination of apparatus and personnel is prevented. Solutions of the fissile and fertile isotopes may be used in combination with solid fuel forms (fuel rods in loaded dissolver solution, for instance). Present experiments involve groupings of fuel rods in water in the presence of additional reflecting materials or plates of neutron poison materials. Planning is underway for experiments with fuel rods in fissile solutions. The following descriptive material deals with these systems as typical examples. The following discussions indicate how safe operation within the limits of the Technical Specifications is achieved with present and planned systems. Heterogeneous assemblies investigated will be engineered and constructed to ensure safe operation within Technical and Operating Specifications in force when they are built.

Investigations of fuel rod systems in water moderator are being conducted in a large 1.8 m x 3 m x 2.1 m deep carbon steel tank located in the critical assembly room. This open-top tank is shown in the photographs of Figures 2, 3 and 4. The tank is equipped with grid plates, a fuel rod support plate, control and safety blades with associated guides and drives, a water dump valve, plus associated electronic, detection and interlock devices.

Figure 2 shows the tank superstructure which supports the safety blade and control blade guides and drive mechanisms. The control and safety blades and drives are similar, but operate independently. During the approach to criticality, when fuel additions are made to the assembly, the control blade is fully inserted and the safety blade remains withdrawn. The inserted control blade maintains the assembly well subcritical, and the cocked safety blade ensures that the reactivity of the assembly can be

Figure 2. Guides and Drive Mechanisms for Safety and Control Blades

Figure 3. Tank Interior Showing Grid Plates for Positioning Fuel Rod Lattices

Figure 4. Fuel Rod Insertion for a Lattice Experiment

further reduced should the need occur. Each blade is independently able to render the assembly subcritical within less than 1.0 second after detection of any need for scram. This is accomplished by releasing the blade from its drive mechanism and allowing it to drop by gravity into the shutdown position where it is stopped without rebound by shock absorbers.

Each blade is driven through a supporting yoke by twin lead screws turned by an electric motor located on top of the tank superstructure. The lead screws are driven synchronously and positively by toothed belts and gears visible in Figure 2. The gearing is presently such that the maximum rates of withdrawal of the control and safety blades are 1.0 and 1.4 cm/sec respectively.

The blades and their supporting yokes are visible in Figure 3. Starting from the top, a beam connects each pair of lead screws and is driven up and down by their rotation. Beneath the beam and attached to it is an electromagnet which holds the blade up until a scram is triggered. Below the electromagnet is a yoke attached to the top of the blade. The ends of this yoke slide on guide rods which maintain blade alignment when the blade is dropped. Guide channels for the lower ends of the blades are located within the tank. Blade drop is arrested without rebound by shock absorbers located on the frame members supporting the lower ends of the lead screws and blade guide rods. The neutron-absorbing lower ends of the blades are varied to suit the needs of the experimental assembly under investigation.

Also visible in Figure 3 are grid plates for positioning fuel rods in a well-defined lattice arrangement. In this picture the tank has been drained, allowing replacement or adjustment of tank internals. During experimentation when the tank is filled with water moderator, gratings are placed above the water level as shown in Figure 4. This facilitates fuel rod loading, which is illustrated in this picture of a lattice of low-enriched uranium rods.

One may note that in Figure 4 the neutron absorbing blades are correctly positioned for fuel manipulations. The lattice is maintained well subcritical by the fully inserted control blade (blade closest to the experimenter). Meanwhile additional shutdown capability is available in the event of any contingency, in the form of the fully withdrawn safety blade (located behind the control blade in the picture). Also visible in Figure 4 are electrical cables connecting flux detectors and control rod position sensors to readout equipment located in the CML control room.

Planning is presently underway for experiments using a fuel rod lattice moderated by fissile solution. The planned experiments will employ control, safety and instrumentation systems as used in previous solution experiments. These experiments will use 12 ft. long fuel rods. Contamination control will be achieved by enclosing the fissile moderator within a specially fabricated tank located within a second large tank. This interior tank will be perforated by a lattice of tubes into which fuel rods may be inserted without contacting the fissile solution. Later experiments may also be carried out in which fuel rods will contact the fissile solution and, of course, become contaminated. For such experiments an appropriate method of contamination control will be selected when the experiments are planned.

The laboratory's existing solution handling system will be used to transfer fissile solutions from storage tanks to the experimental assembly. Features of that system which positively impact the safety of experimentation include filtered venting of all tanks to the hood exhaust system, remote operation from the control room located outside the sealed experimental cell, and capability to rapidly and remotely dump fissile solutions from experimental tanks to storage.

It is to be emphasized that these descriptions of present and planned experimental arrangements are presented as typical examples, and are not meant to be limiting in any way on future experimental arrangements. The examples are presented to indicate how heterogeneous experimental assemblies

are constructed at the CML in accordance with good safety practice, and within the operational safety limits placed upon the facility. Other arrangements are possible.

INSTRUMENTATION

In addition to providing accurate experimental data, CML instrumentation also provides monitoring and control information allowing safe operation of experimental assemblies and response to off-normal situations. Neutron and gamma fluxes are monitored over the entire range of operation, from shutdown to operating power. In addition, dosimeters are located throughout the laboratory to measure flux levels in the unlikely event of an accidental excursion which exceeds the range of operating instrumentation.

Nuclear instrumentation used for experiments with heterogeneous assemblies will be the same as that used for solution and compact experiments. Details of detector location and hook-up will differ, however. Figure 5 indicates schematically the various instrument channels which provide independent and redundant information on the nuclear status of experimental assemblies. Channels used for assembly control (including automatic scram if trip levels are exceeded), health monitoring (including criticality alarm trip if radiation levels become excessive), and data accumulation for experimental analysis are indicated on the schematic. Additional information about this nuclear instrumentation is presented in HW-66266, including discussion of detector sensitivities and use in normal operation.

The instrumentation schematic diagram shows that, except for detectors and associated preamplifiers, the instrumentation is actually located in the control room. The control room instrument console is shown in Figure 6. In addition to instruments and meters, this console contains the controls for critical assembly operation, non-nuclear instrumentation, and the interlock switches and relays which prevent assembly operation unless required instruments are on-line and on-scale, and unless procedural requirements (such as sealing of assembly room doors and vents, and following appropriate operating sequences) are met.

Figure 6. Control Room Instrument Console

Non-nuclear instrumentation includes position indicators for control and safety rods, and for the neutron source used to maintain measurable flux levels in subcritical assemblies. Additional non-nuclear instrumentation monitors temperatures, pressures (including the differential between assembly room and control room), and liquid levels (for solution experiments). A closed circuit television monitors assembly room activities from the control room, and an "intercom" system allows voice communication from the control room to all laboratory areas.

SAFETY AND INTERLOCK SYSTEM

The existence of safe conditions for critical assembly operation in the CML is enforced by a series of interlocking relays and switches which prevent the delivery of electrical power to increase assembly reactivity unless required conditions are met. This interlock system also enforces errorless operation of assemblies. Any manipulation which violates required conditions is automatically detected and the experiment is shut down.

Sealing of the critical assembly room, providing containment for any radioactivity which might be released in a contingency, requires that all doors be closed and that air pressure be delivered to the sealing gaskets of the large door on the south side of the room. Power to operate the heterogeneous assembly described in Section - Site and Facility Description is not supplied until the series of permissive interlocks shown schematically in Figure 7 is satisfied. These interlocks ensure that the room is sealed and that scram switches located within the room are not triggered. This series of interlocks is referred to as the "assembly room relay", and is part of a larger logic network containing dynamic interlocks which is shown in Figure 8.

The dynamic interlock network shown in Figure 8 has two parts. First is a section which monitors flux, and second is a section of procedural interlocks.

The flux monitoring interlock section is shown in Figure 8 from point "A" to "B". It requires continuous monitoring of the nuclear flux at all times during operation. These are the circuits using the flux monitoring channels one through five and the health monitoring channel in the scram circuit shown in Figure 5.

The interlocks form a logic network which requires that at least four flux level trips and one period trip are not bypassed at all times during operation. Three of the flux level trips must be high level trips while one is a low level trip. The low level trip is particularly

Figure 7. Permissive Interlocks

Figure 8. Dynamic Interlocks

important at startup as it provides assurance that sufficient neutrons are available for monitoring the neutron multiplication of the assembly.

The possible combinations of instrument channels which satisfy these requirements may be seen by tracing any path from point "A" to "B". For example, during startup, the minimum requirements are that channels one and two are not bypassed or tripped, one of the level trips on channels three, four, or five is not bypassed, the health monitoring channel is not tripped, and the source is in.

The procedure interlock section is shown in Figure 8 from point "B" to ground. In addition to having power through the flux monitoring interlocks, the interlock requirements for each of the following are:

- 1) Control Rod Withdrawal Power - During experimentation power is supplied to the motor which withdraws the control rod only when the assembly room is sealed, the safety rod is fully withdrawn, and the key switch allowing reactivity addition is set to the reactivity increase position. Alternatively, rod withdrawal can be tested with the assembly room open when it is determined by a senior experimenter that such testing is appropriate. This is accomplished by setting the "Rod Testing" switch to the testing position and setting the key switch to the reactivity increase position. In both cases, to supply power to the control rod drive motor requires operation of the key switch whose key is available only from a senior experimenter.
- 2) Magnet Power - If no scram buttons are pushed, power to energize the magnets attaching the control and safety rods to their drive mechanisms is supplied whenever control rod withdrawal power is available. During experimentation, satisfaction of the assembly room relay allows magnet power supply. During rod testing, magnet power is supplied when the "Rod Testing" switch is in the test position. Magnet power is also supplied during fuel loading, when control rod power is locked out, to hold the safety blade poised for automatic scram if called for by the safety instrumentation interlocks. This requires that the key

switch be set to preclude reactivity increase, and that the control rod be completely inserted. After fuel loading is completed the assembly room relay must be satisfied before the key switch is turned to the reactivity increase position or the safety rod will drop as the key switch turns between its two contact positions.

As is indicated in the above discussions experimental assemblies can be scrammed in various ways. The safety circuit will automatically scram both the safety and control rods whenever any of the following occur during operation:

- Loss of safety circuit power.
- Low or high flux level trip on channel one when not bypassed (a trip on a bypassed channel will not cause a scram).
- Low or high flux level trip or period trip on channel two when not bypassed.
- High flux level trip on channel 3, 4 or 5, when not bypassed.
- Period trip on channel five when not bypassed.
- High flux level trip on the health monitoring channel.
- Low flux level trip on channels 3, 4, or 5, provided that there is no path by which power may be obtained at point "B".
- Opening of the Assembly room door closed relay.

In addition, errors during operation which interrupt the logic of Figure 8 will also automatically trigger a scram. Violating the required flux monitoring conditions by bypassing too many channels or attempting to use a channel not receiving reliable information are examples of such errors. Finally the rods may be manually scrammed by pushing buttons located in the assembly room, the mix room or the control room. Scram buttons are located at two different points on the control console. An

additional button on the safety and interlock panel allows the control rod only to be dropped, if desired (for instance, prior to manual addition of fissile material to a subcritical assembly).

The operability of these safety and interlock systems is established prior to starting operations each day that an experiment is to be conducted. Interruption of electrical power to the magnets attaching control and safety blades to their withdrawal mechanisms is verified as each detection limit is sequentially violated. Blade release is also verified, but only once daily to minimize the number of mechanical shocks to the blade assemblies resulting from arrest of the rapidly falling blades. Every six months measurements are performed to verify the response time of safety devices. Specifically, the time required for full control and safety blade insertion following violation of a trip limit is measured. These tests and measurements ensure the compliance of the safety and instrumentation systems with the requirements of the Technical Specifications.

The interlock system shown in Figure 8 is a further modification of the system originally described in HW-66266 and later modified for use with the remote split-table machine as described in HW-66266, Supplement 1 Revised. To allow experimentation using the appropriate one of these interlock systems, replacable logic panels have been constructed for mounting in the control console. (In the picture of Figure 6 the interlock system logic panels are behind the seated operator. They are partly visible over his shoulder).

Design and operation of the interlock systems presently in use at the CML is based upon the requirements of the Technical Specifications. Construction of heterogeneous assemblies requiring facilities differing from those presently available may cause a need for further modifications to the interlock system. Should this occur, modifications will meet the requirements of the Technical Specifications then in effect. Independent PNL review and approval of such modifications are required prior to experimentation.

ORGANIZATION AND ADMINISTRATIVE CONTROLS

To assure safe and efficient operation of the CML, the responsibilities for facility operation and experimentation are formally defined in the Technical Specifications.¹ The PNL management structure within which the CML is presently operated is shown in Figure 9. Line responsibility for CML operation belongs to the Manager of the CML. He is responsible for formulating, documenting, and administering rigorous safety rules designed to prevent unplanned criticality in the experimental program and to ensure the safety of all operations in the Critical Mass Laboratory.

The safety limits, instrumentation and interlock systems aid the experimenters in safely performing critical experiments. However, even more important to the safe operation of the CML is the knowledge, experience and common sense of the operating personnel. Consequently, the selection, training and qualification of these personnel is of central importance in the administration of nuclear safety at CML. Personnel authorized to conduct critical experiments must be well versed in the methods of critical mass measurements. They must also be familiar with CML control instrumentation and laboratory procedures. In order to safely conduct experiments, such persons will have experience in critical approach techniques and a basic understanding of the hazards and possible consequences resulting from too rapid or too large changes in the assemblies, particularly, the addition of fuel, moderator or reflector materials or the removal of poison materials.

Personnel qualified to conduct critical experiments at the CML are designated senior experimenters. Selection, training and qualification of senior experimenters is described in BNWL-MA-71, Training and Requalification Program for Reactor Operators and Supervisors, Battelle-Northwest Critical Facilities.⁸ Basically, selection is based upon education, physical ability, and mental stability. Training includes study, instruction, and supervised CML operations. Qualification requires satisfactory performance at written and oral examinations, plus a performance examination demonstrating proficiency in facility operation.

Figure 9. Management Chain for CML Operation

Operation of an experimental assembly approaching the critical condition requires the presence in the control room of at least one senior experimenter. The presence of a second person, either a senior experimenter or a qualified operator is also required. Only a senior experimenter, a qualified operator, or a trainee under direct supervision of a qualified operator or senior experimenter may operate the control console. The selection, training and qualification of operators is also described in BNWL-MA-71.

During manual additions of fuel to a heterogeneous assembly a senior experimenter and a qualified operator (or second senior experimenter) must be in attendance. At least one of them must be in the assembly room, and the other may be either in the assembly room or in the control room monitoring the operation.

The administrative requirements described above are taken from the CML Technical Specifications.¹ This document also specifies requirements for review and audit of CML operation by the Battelle Nuclear Safety organization, as indicated in Figure 9. Nuclear safety must review and concur in: supplements to the CML Safety Analysis Report, proposed facility design changes, procedures that involve a change in the Technical Specifications, and proposed tests and experiments.

For each new type of experiment a written request must be submitted to the Manager of the CML. This request must contain a statement of the purpose of the experiment and the measurement methods to be used. It must also describe fissionable material form and preparation, special safety devices to be used, and neutron measurement instrumentation. Any unusual hazards which might be associated with the experiment must be described, and personnel to be involved must be listed. Authorization for experimentation requires approval of the Manager of the CML, review and concurrence by Nuclear Safety, and approval by the Manager of the Energy Systems Department.

ANALYSIS OF SYSTEM HAZARDS

A. Contingencies Relating to Nuclear Criticality

Fissionable materials in the forms of solids and solutions will be used as fuel for heterogeneous assembly experiments. The fuel will contain one or more of the fissile isotopes ^{233}U , ^{235}U , and ^{239}Pu - ^{241}Pu ; plus the fertile isotopes Th and ^{238}U . The permissible forms for solid fuels are powders, compacted powders, sintered pellets, metals and alloys. Powder fuels will be contained so that geometrical configuration is maintained and contamination of apparatus and personnel is prevented. Solutions of the fissile and fertile isotopes may be used in combination with solid fuel forms (fuel rods in loaded dissolver solution, for instance).

Due to the presence of quantities of fissionable materials at the CML it is possible that unintentional assembly of a critical mass could take place. The possibility that operations related to experimentation using heterogeneous assemblies could lead to an unintended criticality are examined in this section. Contingencies arising from operations, and from natural disasters are discussed. It is concluded that laboratory and personnel safety are adequately provided by the combination of engineered and administrative safety limits enforced at the CML.

1. Manual loading of fuel

In this section the operations and procedures involved in the addition of fuel to an experimental assembly are described. Errors and failures which would be necessary for criticality to occur are identified. It is concluded that the combination of procedures and safety circuitry provides adequately for the safety of personnel involved in experiments with heterogeneous assemblies.

The critical condition of an assembly is determined by adding small increments of reactivity, starting with an assembly known from calculations or previous experimentation to be well subcritical.

During the approach to critical the neutron flux in the assembly (due to either an extraneous neutron source or to neutron emission from the fuel) is measured following each reactivity addition. Inverse multiplication curves are plotted and used to predict the critical size of the system while it is still subcritical. Such curves are plotted for each of at least two separate neutron counters, by two persons, each of whom calculates the curves independently. Agreement is required between calculated values independently obtained before additional fuel is loaded. Also, the shape of the neutron multiplication curves must agree with that expected for a critical approach. Therefore, two qualified people working independently would have to make simultaneous and approximately equal errors in calculating and plotting inverse multiplication curves for an attempt to be made to load (mistakenly) too much fuel.

During fuel additions to an assembly, control rod(s) are in the inserted position to maintain the assembly well subcritical. Once the fuel is loaded the critical assembly room is vacated and doors and vents are closed for containment. Reactivity is then added remotely, by withdrawing the control rod(s). Inverse multiplication curves are plotted for both the "rods in" and "rods out" condition, allowing evaluation of control rod worth in terms of excess fuel required for criticality with the rods in. The current Technical Specifications limit fuel additions to, "less than 85% of the increment predicted to achieve criticality with the control device(s) in that position for which the experimental assembly is in its least reactive condition." The "rods in" and "rods out" curves provide the information needed to keep operations within this limit as criticality is approached and achieved.

During fuel loading a safety rod is poised over the assembly, ready to drop and reduce assembly reactivity even if the controls described above are violated. The current Technical Specifications

require this rod to be capable of rendering the assembly subcritical within 1.0 seconds, including safety circuit delay. The safety circuit which triggers safety rod drop is required by the current Technical Specifications to contain two independent and operable detector channels monitoring flux levels in the assembly, plus a third channel monitoring the flux period (rate of change of flux). Rapid insertion of fissionable material is normally sufficient to cause a "period trip" that drops the safety rod even in assemblies that are far subcritical.

As has been previously noted, the safe operation of the CML depends primarily upon the operating personnel. The careful selection and training of operating personnel ensures that manual fuel loading will be performed by persons who understand what they are doing, why they are performing each operation, and what the consequences of errors can be. Furthermore, a decision to load the wrong amount of fuel has been shown to require independent mistakes of the same magnitude by two such persons. Nevertheless, should such a combination of errors occur, aural feedback would warn the operators of approaching trouble, and three separate safety instrumentation channels operate to detect and automatically respond to abnormal flux rates or increases of flux. Manual reduction of assembly reactivity is available to operators if unsafe conditions are detected (or even suspected) by pressing "scram" buttons located on either the control console or in the assembly room. In addition each of the safety instrumentation channels independently triggers safety rod drop when preset limits are exceeded, with full safety rod insertion taking place in a time which is short compared to that required for manual operations. Thus the careful design and construction of critical assemblies by well trained, responsible personnel is reinforced by formalized procedures, extensive instrumentation, and engineered laboratory design all focused on the goal of safe laboratory operation.

Hence it is concluded that the safety of CML and other site personnel, and of the general public, is more than adequately ensured by this in-depth combination of factors.

2. Water flooding

The Critical Mass Laboratory is situated on the 200 Area plateau of the Hanford Reservation. The report A Preliminary Safety Analysis of Near Surface Storage of Radioactive Waste as Salt Cakes, BNWL-1194⁹ concluded that the 200 Areas are well protected from the effects of weather, earthquakes, floods, earth slides, and future dam construction on the Columbia River. In particular " ... a coincident failure of Grand Coulee Dam and the simultaneous breach flows from upper Canadian storage projects, would produce a flow of only 10 million cfs past Hanford. Even this flow rate would raise the surface waters to an elevation only 560' above sea level." The Assembly Room floor level is 683" above sea level.

Sources of water at the CML which could cause flooding of the critical assembly room are identified in this section, along with the design features which prevent water accumulation to a depth exceeding six inches in the critical assembly room. Storage of fissile fuel is designed to be safe under conditions of complete flooding. Experimental assemblies will be designed so that a six inch deep accumulation of water on the assembly room floor cannot cause unplanned criticality. Consequently the performance of heterogeneous experiments does not increase the extremely small potential for criticality accidents caused by flooding.

Water sources inside the critical assembly room include the fire control sprinkler system, the current experimental tank containing water moderator, and the water and steam supply lines.

The water supply to the fire control sprinkler system in the assembly room is limited to 500 gallons. Chilled water is circulated through coils in the heating/cooling unit by a recirculating loop which contains less than 100 gallons of water. The current experimental tank has a capacity of 3100 gallons. Release of any one of these water sources onto the assembly room floor would yield a water depth not exceeding six inches.

Water sources which are not limited are: one water supply line, entering through the West wall, which has about one foot of pipe plus a faucet inside the room; a single safety shower line, also entering through the West wall, which has less than five feet of pipe plus a shower head inside the room; and steam lines for heating. However, water cannot collect in the critical assembly room to a depth of more than six inches when the containment door is open. That is the depth of the lip of the entrance passageway. When the water reaches six inches deep it will start running out through the entrance passageway, and leave the building.

Therefore, flooding of the assembly room to a depth exceeding six inches is possible only when the containment door is closed and the room is sealed. This occurs only during experimentation, when the building is occupied. The lockable door used to secure the assembly room during off hours, and the nearby outside door are not water tight. Water leaking from the building during off-hours would be detected during security checks made during each 2 hour period. This would enable prompt corrective action to be taken.

When the containment door is sealed, personnel are excluded from the room. Consequently, no mechanism exists for opening the valves in the water lines. Only a physical break in a water or steam supply line could lead to water from a non-limited source being released in the assembly room. It is extremely unlikely

that a significant supply line leak could occur when the assembly room is in confinement status, and that it could go undetected by TV and aural monitors for a long enough time that water could accumulate to a depth greater than six inches.

Hence it is concluded that the performance of experiments with heterogeneous assemblies has not increased the extremely small potential for criticality accidents caused by flooding.

3. Fire

There is very little risk of fire in the Assembly Room because combustibles are required to be kept to the lowest practical minimum. The building is constructed primarily of concrete and steel. Should a fire occur, the Assembly Room is equipped with an automatic deluge sprinkler system. (This fire protection system is discussed in the original hazards summary report, HW-66266).⁵ Due to the construction, and the sprinkler system, the probability is extremely low that a fire would be of sufficient intensity to cause rearrangement of any portion of the fissionable material into a critical assembly. Buildup of water from fire fighting operations has already been covered under flooding. Section 10 of PNL-MA-25⁴ discusses criticality safety in fire fighting. The Assembly Room is designated as Category C for fire fighting purposes. In these areas the use of water is limited to high expansion foam, automatic sprinkler systems or hose fog nozzles. Hence it is concluded that the performance of heterogeneous experiments creates no additional hazards due to fire at the Critical Mass Laboratory.

4. Explosion

There is no known explosive potential in the Assembly Room.

5. Loss of Services

Electricity is the only service that has any direct relationship to criticality safety. Control and safety systems plus control room instrumentation depend upon continuous electrical supply for normal operation. If power is lost even momentarily, the control and safety devices are designed and routinely tested to assure fail-safe operation, whereby they immediately scram the system to its least reactive condition. The entire system is engineered so that loss of power will shut everything down safely. Furthermore, an extended period of loss should not occur since an emergency power supply which is automatically activated upon loss of normal power supply is provided to maintain vital lighting, ventilation, fire protection equipment, monitors, alarms, controls and other safety features.

Other services which could be lost in either the Assembly Room or Control Room are ventilation, water, steam, heating and cooling. None of these services have any effect on criticality safety if they are lost. Hence it is concluded that the performance of heterogeneous experiments creates no additional hazards due to loss of services at the Critical Mass Laboratory.

6. Earthquake

It is highly unlikely that criticality within the assembly room could result from an earthquake. The design of fuel storage arrays includes analyses to ensure that potential effects of earthquakes cannot result in criticality.

Experimental assembly designs are not analyzed to demonstrate immunity to earthquake forces. Nevertheless, the assemblies contain sturdy positioning devices which will maintain relative spacings of components under conceivable motions of the assembly room floor. Furthermore, they are brought near the critical

condition for only relatively short periods of time. And they are operated under specifications which: limit the amount of excess reactivity present in an assembly, ensure the presence of adequate shutdown margin, ensure automatic assembly scram on power loss, and ensure the presence of a qualified senior experimenter whenever an assembly is in other than a deactivated condition.

In the extremely unlikely situation that an earthquake occurred while an assembly was in the critical condition, control and safety blades would be dropped by the operator to terminate the chain reaction. Both blades and guides are rigid, and the guides are solidly attached to the tank. The massive construction of the assembly room assures that no differential forces will be transmitted to the assembly. Consequently tank and contents will move as a unit, without distortion, and safety rods will function properly.

In addition, even if unplanned criticality did occur in an assembly there are several factors which would strongly limit the consequences. Most important is the limitation of excess reactivity, which prevents prompt criticality from occurring. This assures that operators and experimenters have time to react to the situation before power levels in the assembly become excessive. During critical assembly operation two qualified operators, one of whom is a senior experimenter, are required to be present in the control room. Having designed and constructed the assembly, these operators are intimately familiar with it and can shut it down by various methods. For instance, in addition to scrambling control and safety blades, with the present set-up the large valve seen in the foreground of Figure 2 can be opened and the water moderator drained from the experimental tank. This valve can be remotely operated from the control room without opening the containment. In future experiments using fuel rods and fissile solutions, opening this valve would drain water reflector from around the interior tank

containing fissile solution. In addition, the fissile solution could be remotely drained from the experimental tank into the solution storage tanks.

Thus it is extremely unlikely that an earthquake could trigger an unplanned criticality in the assembly room. Should this happen, however, the assembly would be shut down remotely from the control room. In addition, the structural integrity, of the massive assembly room construction assures containment of the effects of any excursion up to the maximum credible nuclear burst of 3×10^{18} fissions (see Section -- Consequences of Accidents for discussion of this accident). Hence it is concluded that the safety of CML and other site personnel and of the general public is adequately provided for by this combination of factors.

B. Other Potential Hazards and Accidents

The Critical Mass Laboratory is operated in conformance with applicable requirements specified in Section 12, Safety and Security, Battelle-Pacific Northwest Division Management Guide¹⁰ and applicable BNWL-MA series administration manuals referenced therein. Hazards discussed in this section include radiation exposure of personnel and releases within the assembly room and to the environment.

1. Radiation Exposure to Personnel

Human exposure to ionizing radiation from both internal and external sources is to be kept as low as practicable through application of the best protective equipment, methods, and designs technically and economically feasible. To accomplish this objective, a radiation protection program is established and other requirements are specified that shall conform with Management Guide 12.4, "Radiation Protection." The operation of the Critical Mass Laboratory conforms to applicable requirements in

the manual Radiation Protection Procedures, BNWL-MA-6¹¹ regardless of the type of experiments being performed.

2. Potential Releases Within the Assembly Room

The possibility of breaching the fuel rod cladding or of releasing contamination within the Assembly Room always exists. The resulting hazard of contamination spread inside the Assembly Room ranges from minimal for metallic or alloyed fuels to potentially serious for compacted powder fuels. Various controls are in force that will limit the release and spread of contamination from such accidents. Examples are care and caution in handling fuel elements, the wearing of protective clothing, gloves and masks as appropriate, the use of step-off procedures, and personnel and work area monitoring procedures. Additional information on currently required controls is available in BNWL-MA-6. These controls are enforced regardless of the type of experiments being performed.

3. Potential Releases to the Environment

Discharge of solid, liquid, and gaseous waste products into the environment shall meet all applicable Federal, State, and local regulations. Within these regulations all discharges of material shall be limited to the lowest practical level. To accomplish this objective, a waste management program is established and other requirements are specified that shall conform with Management Guide 12.9, "Waste Management." The operation of the Critical Mass Laboratory conforms to applicable requirements in the manual Waste Management, BNWL-MA-8¹² regardless of the type of experiments being performed.

A common exhaust system, serving the Assembly Room and the Mix Room, is provided to eliminate the spread of any airborne contamination to the outside environment. Air flow is treated

by two stages of High Efficiency Particulate Air (HEPA) Filters. Heterogeneous experiments have no greater potential for causing airborne contamination in the Assembly Room than solution and compact experiments. Consequently they will not increase the potential for release to the environment over that which already exists. Due to the containment capabilities of the Assembly Room this potential is quite low.

CONSEQUENCES OF ACCIDENTS

A. Energy Release of the Maximum Credible Burst

The assembly room within which critical experiments are performed was designed to contain the effects of a postulated nuclear burst producing 3×10^{18} fissions. This burst was assumed to be the Maximum Credible Burst for experiments with homogeneous assemblies, and was analyzed as such in the original hazards analysis presented in HW-66266. For reasons explained in the following discussion, this burst of 3×10^{18} fissions is also assumed to be the Maximum Credible Burst for experiments with heterogeneous assemblies.

The nuclear burst associated with the January, 1961 accident at the SL-1 Reactor is believed to have had a magnitude of 1.5×10^{18} fissions.¹³ "The evidence strongly indicates a nuclear incident of 50 megawatt-seconds, or more, which could credibly have been induced by rapid and extensive motion of the central control rod." Apparently operators struggling to move a stuck control rod succeeded suddenly, and overshot badly. The three men in the cell were killed by effects of the steam explosion. This accident occurred at a reactor designed to operate at a power of 3 MWt for three years without refueling. At the time of the accident less than half of the core life had been used, and a large amount of excess reactivity was available upon control rod withdrawal. This is in sharp contrast to assemblies allowed in the CML, in which excess reactivity is limited to preclude the attainment of prompt criticality regardless of control rod and/or safety rod manipulations. The fact that the burst associated with the SL-1 accident is smaller than that assumed here for the Maximum Credible Burst strongly supports the conservatism of the assumed burst.

The nuclear burst associated with the destructive test of the SPERT-I reactor¹⁴ had a magnitude of 1×10^{18} fissions (31 megawatt-seconds). That this burst is smaller than the Maximum Credible Burst assumed here also strongly supports the conservatism of that assumption.

It is instructive to review what was required to bring about the SPERT-I destructive test. The nuclear burst was initiated by the pneumatic ejection of a poison rod. This required only 85 milliseconds, and inserted 3.5 dollars of reactivity (one dollar being the excess reactivity insertion required to make the core prompt critical). The result of this massive reactivity insertion was the establishment of an exponential power increase with a period of 3.2 milliseconds, which caused extensive melting of the fuel and was terminated by a steam explosion which destroyed the core. Such a reactivity insertion is not credible in the assemblies to be investigated in the CML.

The preceding paragraphs should not be interpreted to imply that nuclear bursts exceeding 3×10^{18} fissions cannot be produced in heterogeneous assemblies. The BORAX-I destructive test¹⁵ yielded 4.2×10^{18} fissions in an energy release of 135 megawatt-seconds. This resulted from a larger reactivity insertion, which established a power increase having a period of only 2.6 milliseconds. However, the production of such bursts requires assemblies and actions which violate CML Technical Specifications by such a great extent that such bursts are not considered credible.

B. Blast Effects of the Maximum Credible Burst

In the original hazards analysis for the CML, HW-66266, blast effects were ignored because, "In solution experiments there is no evidence of blast effects of such magnitude to cause concern for the laboratory integrity in the event of a burst." However, in the SL-1 accident and in the BORAX-I and SPERT-I destructive tests, facility damage was sustained in addition to reactor core damage or destruction. In the following paragraphs the causes of blast effects are discussed and an argument is presented which indicates that blast effects from credible nuclear excursions at the CML will not jeopardize the integrity of the facility.

In homogeneous assemblies fission energy is deposited uniformly in both fuel and moderator, causing radiolytic decomposition of the moderator and raising the temperature of both simultaneously. However, in heterogeneous assemblies of fuel rods in water moderator, fission energy is deposited primarily in the fuel, with thermal transfer required to get it to the moderator. Consequently, during a prompt nuclear excursion the fuel can become quite hot, or even molten, before significant heating of the water moderator occurs. When the reactivity insertion causing the excursion exceeds the compensatory effects of radiolytic decomposition and of any negative temperature coefficient of reactivity of the fuel, termination of the excursion requires the expansion, boiling or expulsion of the moderator caused by heat transfer from the fuel. Two effects of this are that higher power levels may be reached due to time delay associated with heat transfer, and that violent interactions between molten fuel and moderator become possible. The combination of these effects led to the reactor and facility damage produced in the SL-1 accident and in the BORAX-I and SPERT-I destructive tests.

Heterogeneous assemblies of fuel rods in fissile solutions retain the favorable property that energy released by fissions in the solution is deposited there directly and immediately. Consequently radiolytic decomposition of the moderator is greater than for fuel rod-water lattices. Volumetric heating and expansion of the moderator is also greater, and it occurs faster. Since these are the effects which terminate prompt excursions in lattices moderated by both water and fissile solutions, shut-down will be faster and more positive with fissile solution moderation. Neither energy release nor blast effects will exceed effects postulated for rod-water systems. The following discussion is therefore confined to rod-water systems.

Explosive effects were first encountered in the BORAX-I series of tests.¹⁵ Non-destructive tests had been carried out over the range of reactor periods from 100 milliseconds to 5 milliseconds. Then, when the period was further reduced to 2.6 milliseconds (by increasing the reactivity insertion) an explosion occurred causing such damage that details of its occurrence were lost.

"The destructive program in SPERT-I, therefore, had as its objective a systematic exploration of the destructive region of reactivity insertions in order to describe damage effects encountered, to search for any explosive threshold, and finally to demonstrate a full-scale explosion in an effort to contribute to the understanding of these responses and consequences."¹⁴

Prior to the destructive test in SPERT-I, a series of tests was performed with smaller, but increasing, reactivity insertions. Warping of the fuel plates was first observed following an excursion having a period of 7 milliseconds. (The fuel was aluminum-clad highly enriched U-Al metal alloy in plate form). After an excursion with a 5 millisecond period (2.6 dollar reactivity insertion) molten fuel was observed to have leaked through cracks in the fuel cladding in the central core region. Reducing the excursion period to 4.6 milliseconds (2.8 dollar reactivity insertion) yielded melting of the fuel cladding in the core center. Fuel damage was so extensive that 80% of the fuel plates required replacement prior to the final destructive test.

"Although damage from thermal deformation had been produced in nearly 80 percent of the core and melting in about 3 percent, neither of these phenomena had produced a tendency toward the generation of large pressures despite the fact that fuel plate temperatures in many cases exceeded the critical temperature [the temperature above which water vaporizes at any pressure] of water."¹⁴

In the final destructive test the reactor power peaked and then dropped (due to steam void formation) just as it had in previous tests. However, 15 milliseconds after the power peaked a very high pressure pulse was generated which destroyed the reactor. It is believed that two factors were involved in causing the pulse.¹⁶ First, a water-hammer effect from vapor-blanket collapse is believed to have dispersed molten metal fuel into surrounding water causing both chemical energy release and rapid, efficient heat transfer to the water. And second, pressure amplification occurred in the core periphery by a second water-hammer effect caused by bubble collapse under the driving pressure from the central region.

For the purposes of this discussion the mechanism of pressure pulse generation is unimportant. What is important, is that pressure pulse generation requires massive reactivity insertion occurring extremely rapidly. Neither the amount nor the rapidity of reactivity insertion required to initiate blast effects are allowed in heterogeneous assemblies to be studied at the CML, and the simultaneous occurrence of both is not considered credible. Therefore, the integrity of the 35 x 35 x 20 foot reinforced concrete critical assembly cell, which has walls three and five feet thick and ceiling and floors two feet thick, will not be jeopardized by blast effects from credible nuclear excursions. This conclusion is the same as that which was reached for homogeneous experiments.

C. Estimated Consequences of the Maximum Credible Burst

As was discussed in the preceding sections, the Maximum Credible Burst assumed for heterogeneous assemblies is the same as that assumed in HW-66266 for homogeneous systems. Also, blast effects of sufficient magnitude to jeopardize the integrity of the experimental cell are not considered credible for heterogeneous or homogeneous assemblies. Therefore, the estimated consequences are unchanged from those presented in HW-66266. For the sake of completeness they are summarized below:

Radiation doses from the burst, estimated for personnel outside the experimental cell, are listed in Table I, taken from HW-66266. The maximum dose is for an individual located at the shield wall, and is less than 2 rems.

In HW-66266 an assessment was made of the effects of release of 10 percent of the gross fission products resulting from the Maximum Credible Burst. Despite the improbability of containment failure, it was simply assumed to occur due to an unspecified cause. For homogeneous systems it was assumed that a 10 percent release would result. Releases from heterogeneous assemblies should be lower than from solutions, however, due to barriers such as cladding. Therefore that assumption is conservative for heterogeneous systems. Table II taken from HW-66266 presents the results of a conservative analysis of a 10 percent release. Downwind doses at locations of built-up areas (Purex ~ 3000 feet SW; Power House ~ 3000 feet SE) are low except for the case of a strong temperature inversion. In twenty years of operation the CML has never experienced an unplanned criticality. Should one occur, the maximum credible nuclear burst does not jeopardize the integrity of the assembly room. Furthermore, inversions are primarily nighttime phenomena and laboratory operation is normally during the day shift. Consequently, the probability of coincident containment failure and occurrence of a strong inversion is judged to be extremely low.

Therefore, it is concluded that the performance of critical experiments with heterogeneous assemblies at the CML presents no unusual hazard to other major facilities in the area, nor does it result in undue hazards to the operating personnel of the Critical Mass Laboratory.

TABLE I

TOTAL DOSES AT VARIOUS DISTANCES FROM OUTER EDGE OF SHIELD
RESULTING FROM 3.0×10^{18} FISSIONS

(All Doses Given in Milli-rads Except as Noted)

<u>Distance from Shield (Ft)</u>	<u>From Direct Beam Gammas</u>	<u>From Sky- Shine Gammas</u>	<u>From Direct Beam Neutrons</u>	<u>Total (Milli-rads)</u>	<u>Total (Milli-rems)</u>
0	5.0	0	170	175.	1705
20	10.3	0.53	35.6	46.4	367
40	4.5	8.3	15.4	28.2	167
60	2.5	9.0	8.1	19.6	93
80	1.54	8.6	4.9	15.0	59

TABEL II

CALCULATED RADIATION DOSES ON PLUME CENTER LINE

Distance Feet	Dose from Ground		Inhalation					(b) Cloud width 0.1 conc. Points Feet
	Dose from Cloud r	In One Hour r	Rate at 24 Hours mr/hr	Lung Dose (a)		Thyroid Dose rads	Plutonium Retention μ c	
				FP rads	Pu rem			
<u>Strong Inversion</u>								
160	60-20	0.2-0.7	3-9	50-20	1200-400	300-100	0.8-0.3	43
330	30-17	0.1-0.5	2-6	30- 8	600-200	200- 50	0.5-0.1	79
660	24-12	0.1-0.2	2-3	20- 3	400- 70	100- 20	0.3-0.05	130
1300	12- 7	0.07-0.1	2-1	12- 1	200- 30	60- 8	0.2-0.02	230
2600	5	0.03-0.006	<1	6- 0.6	120- 15	30- 4	0.08-0.01	390
5300	2	0.01-0.003	<1	3- 0.3	60- 8	20.2	0.04-0.006	700
<u>Moderate Inversion</u>								
160	4-2	0.02-0.08	<1	3-1	70-30	20- 8	0.05-0.02	43
330	2-1	0.01-0.06	<1	2-0.5	40-14	10- 4	0.03-0.01	79
660	1	<0.01-0.03	<1	0.8-0.2	20- 6	5- 2	0.01-0.004	130
1300	0.3-0.5	< 0.01	<1	0.3-0.08	6- 2	2- 0.6	0.004-0.002	230
2600	0.2-0.3	< 0.01	<1	0.2-0.03	4- 0.8	1- 0.2	0.003-<10 ⁻³	390
5300	0.06-0.09	< 0.01	<1	0.1-0.02	2- 0.4	0.6- 0.1	0.002-<10 ⁻³	700
<u>Neutral</u>								
160	3-0.6	0.02-0.03	<1	2-0.3	40- 7	10- 2	0.03-0.005	66
330	1-0.3	< 0.01-0.03	<1	0.7-0.08	20 -2	5- 0.6	0.01-0.002	120
660	0.4-0.2	< 0.01	<1	0.2-0.03	5- 0.6	1- 0.2	0.004-<10 ⁻³	220
1300	0.1-0.08	< 0.01	<1	0.08-0.01	2- 0.2	0.4-0.05	0.001-<10 ⁻³	400
2600	0.03-0.04	< 0.01	<1	0.02-<0.01	0.4-0.06	0.1-0.02	<10 ⁻³	700
5300	0.006	< 0.01	<1	<0.01	0.1-0.02	0.04-<0.01	<10 ⁻³	1300

(a) One-half delivered in first year.

(b) Full cloud width.

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