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QUARTERLY TECHNICAL PROGRESS REPORT

REACTOR SAFETY

APRIL – JUNE 1978

DOE Research and Development Report

Prepared for the United States
Department of Energy
Division of Reactor Research and Technology,
under Contract Number EY-76-C-03-0824

Rockwell International
Atomics International Division
Energy Systems Group
8900 DeSoto Avenue
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The preceding Progress Report was AI-ERDA-13234

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Program:	LMFBR Safety		
DOE Task:	Task 28, Reactor Safety – Accident Debris Behavior		
Program Manager:	R. E. Schnurstein	**Project Manager:**	H. A. Morewitz
Reporting Period:	April - June 1978	**Category:**	
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Principal Investigators: R. P. Johnson, C. T. Nelson, E. U. Vaughan, and C. Guderjahn

I. PROJECT OBJECTIVES

1) Conduct tests that will characterize the behavior of sodium oxide, fuel, fission product, and other aerosols as they might be generated by various postulated LMFBR accidents.

2) Determine by analysis and confirm by experiment the generation and transport of these aerosols with respect to source (location, type, and configuration), for the entire course of events associated with real and hypothetical accident conditions.

3) Conduct tests that will determine the effect of molten fuel on reactor structural or sacrificial material.

4) Perform LMFBR risk assessments of key LOA-3 and LOA-4 scenarios to provide a basis for prioritizing the various Atomics International (AI) Division of the Energy Systems Group of Rockwell International safety projects so that they will have the maximum design applicability and value.

II. MAJOR ACCOMPLISHMENTS DURING FISCAL YEAR 1978

Several important mechanisms that reduce the consequences of fast reactor HCDA's have been investigated. Tests with both UO_2 and sodium oxide aerosols have shown that turbulent, high concentration aerosols quickly form large agglomerates. In addition, leak paths through broken or displaced reactor head

seals would be rapidly plugged (following a HCDA) by the aerosol debris passing through. Further, most of those aerosols that do pass through would be agglomerated into large size particles, which would fall out in the reactor containment building.

UO_2 has been successfully arc melted and poured onto graphite, concrete, carbon steel, and stainless steel. The molten UO_2 spread quickly and solidified in a coolable configuration without penetrating the underlying material. Thus, molten fuel resulting from a hypothetical core meltdown would spread out into a thin layer on the reactor cavity floor.

III. PROGRESS DURING REPORT PERIOD

A. SUBTASK D – HIGH TEMPERATURE-CONCENTRATION AEROSOLS

1. Introduction

Certain types of hypothetical reactor accidents in LMFBR's could produce large amounts of aerosolized fuel debris mixed with sodium vapor and fission gas. The accompanying sodium slug motion would stretch the head tiedown bolts allowing the aerosol mixture that reached the cover gas to escape into the reactor containment building. The radiological hazard associated with such airborne debris is reduced due to the increase in size of the agglomerated particles. Large particles cannot easily escape through leaks, and those that do, fall out rapidly. Also, even if inhaled, insoluble particles above 10 μm aerodynamic diameter (AED) are readily eliminated from the lungs and from the body by natural processes.*

Attempts are being made to assess the proportion of aerosol particles escaping through broken or displaced head seals and the size of particles that do escape.

Previously, plugging of leak paths has been demonstrated for both sodium oxide and uranium oxide. During this report period, tests were carried out to measure the size and concentration of uranium oxide as produced in the tank of

*P. E. Morrow, et al., "Deposition and Retention Models for Internal Dosimetry of the Human Respiratory Tract," Health Physics 12, 172 (1966)

the arc melter. The intensely hot arc vaporizes copious amounts of uranium oxide, which then condense in the argon furnace atmosphere to form particulates.

2. Fallout Measurements

A turntable was constructed to determine fallout as a function of time. The collector is a horizontal wheel, which slowly turns at a known rate. The wheel carries 12 glass slides, which are exposed to the furnace atmosphere one by one at 3-s intervals. The mass collected is measured by weighing the slides before and after exposure.

The furnace was operated at 1/2 atmosphere pressure of argon with a slow flow of argon into the furnace. The current was increased to 3000 A at 40 V, and the usual dense cloud of particulates completely obscured the arc. The current was then turned off, and the argon flow into the furnace was also valved off.

At the same time, the wheel was started in order to collect fallout. Table 1 and Figure 1 give the results. The concentration of aerosol within the tank at

TABLE 1

FALLOUT OF UO_2 VS TIME IN THE ARC MELTER TANK*

Slide No.	Time of Slide Exposure After Arc Turn Off (s)			UO_2 Collected (mg)
	Begin	End	Average	
1	1.5	4.5	3.0	4.33
2	4.5	7.5	6.0	2.55
3	7.5	10.5	9.0	0.78
4	10.5	13.5	12.0	0.40
5	13.5	16.5	15.0	0.62
6	16.5	19.5	18.0	0.21
7	19.5	22.5	21.0	0.72
8	22.5	25.5	24.0	0.50

*Tank ID = 105.4 cm
Tank Length = 123.8 cm
Tank Volume = 1.08 m^3
Slide Area = 4.9 cm^2
Vertical Distance of Slide to Tank Top = 63.5 cm

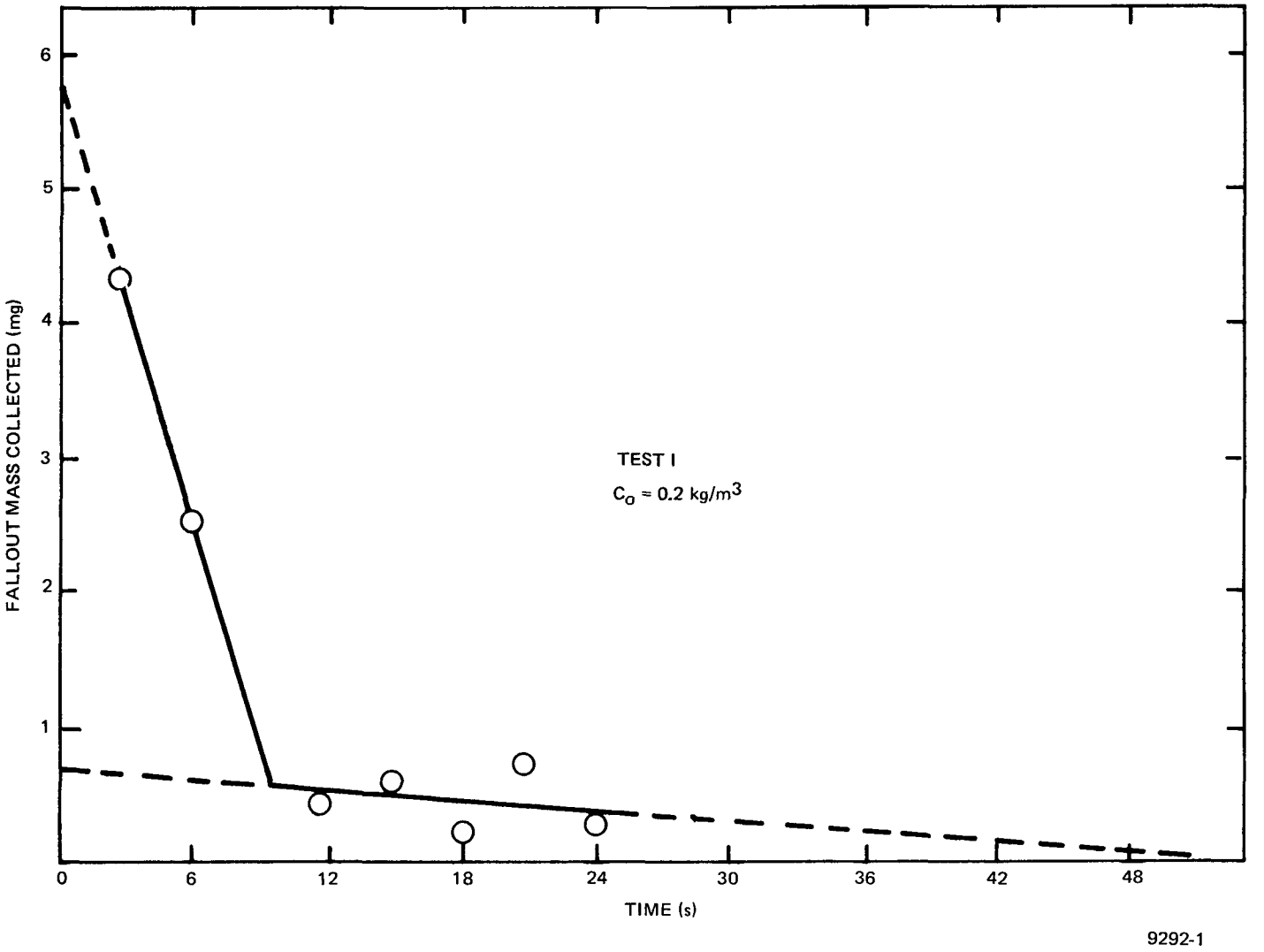

Figure 1. UO_2 Fallout vs Time (Test I)

the instant the arc was turned off may be estimated from Figure 1 by integrating under the curve. The integrated mass of material collected is 61 mg, and the collection volume above each slide is $3.1 \times 10^{-4} m^3$. This gives a concentration of 0.2 kg/m^3. The vaporization rate can also be estimated. As the arc melter tank volume is about 1 m^3, there is about 0.2 kg of UO_2 suspended within the tank at any time. From Figure 1, the initial slope of the curve indicates that this amount of material must fall out in 10 s. Thus, the vaporization rate is about 0.02 kg/s when the furnace is operated at 3000 A and 40 V. The heat required for vaporization of 0.02 kg/s of UO_2 is about 68 kW or 1/2 of the furnace input power.

The UO_2 particles sometimes form long chain agglomerates. Figure 2 shows a 100 X enlargement of a long chain particle collected on one of the slides. As expected, larger particles fall out earlier. The particles collected on the first fallout slide are roughly 40 μm in average projected diameter while on Slide No. 8, the particles are roughly 15 μm in average projected diameter.

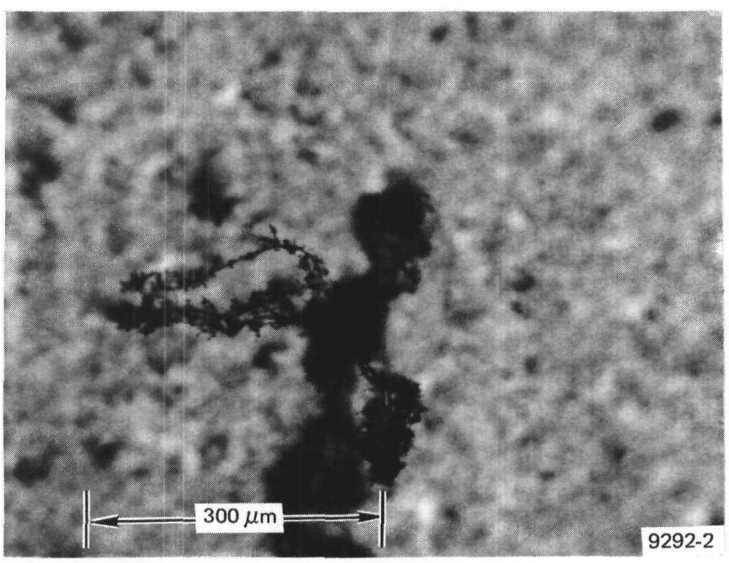

Figure 2. Long Chain UO_2 Particle Formed in Arc Melting Furnace at C_o = 0.2 kg/m^3

B. SUBTASK F – LARGE-SCALE MOLTEN FUEL TESTS

These tests involved arc melting and pouring of UO_2 onto reactor structural materials to simulate the aftermath of an LMFBR CDA. The arc melting furnace has been described previously.* Briefly, it consists of a water-cooled copper crucible filled with UO_2 and a graphite-tipped electrode above, all enclosed in a large water-cooled tank. A high-current arc is passed between the UO_2 and the electrode in order to heat and melt the UO_2. The crucible is then tipped and the molten UO_2 pours onto the test item below.

In previous tests, UO_2 has been melted and poured onto graphite, carbon steel, and stainless steel plates. During the current report period, further pours onto a stainless steel plate and a pour onto concrete were made. The purpose of the stainless steel tests was to establish scaling laws and to verify heat transfer calibration. The pour onto concrete was a scoping test needed to plan further investigations of post-accident heat removal.

In Tests F, G, and H, three successive pours of UO_2 were made on the same plate of Type 304 stainless steel. The plate was a rectangle of dimensions 10 in. by 10-7/8 in. by 5/8 in. thick (25 cm by 28 cm by 1.59 cm thick). The plate had a steel rim placed around the outer edge to confine the molten UO_2 to the top surface. The plate has considerably less area than those used previously in order to increase the thickness of the UO_2 on the surface. Figure 3 shows the plate covered with UO_2 from Test G. After removal of the UO_2, the plate was discolored and slightly warped, but otherwise undamaged (Figure 4).

In Test H, a thin copper cover (0.25 mm thick) was placed over the rim of the plate. The purpose of this cover was to prevent the buildup of an insulating layer of UO_2 powder on the plate during the melting process before the pour. Figure 5 shows the surface after Test H. Evidently, copper vapor bubbled up through the UO_2 and left the surface quite rough.

Thermocouples were embedded in the plate to measure the temperature rise during the pour. The thermocouples were placed as shown in Figure 6.

*Staff, "Annual Technical Progress Report, LMFBR Safety Program, GFY 1976 and 1976T," AI-ERDA-13182 (January 10, 1977)

Figure 3. Stainless Steel Plate Covered with UO_2 (Test G)

Figure 4. Stainless Steel Plate After Removal of UO_2

Figure 5. Stainless Steel Plate Covered with UO_2 (A thin copper sheet covered the plate previous to the pour.)

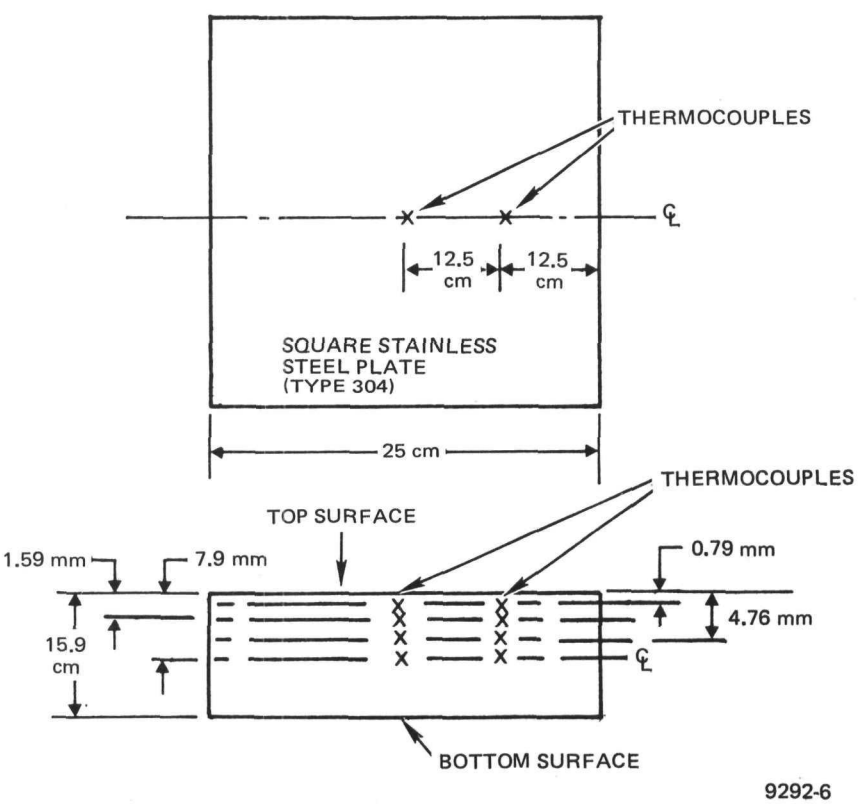

Figure 6. Thermocouple Locations for Tests F, G, and H

Figure 7 shows the recorded temperature vs time for four thermocouples in the center group. The thermocouple nearest the surface malfunctioned during the test, apparently breaking and then reestablishing contact. The other thermocouples performed well and indicate a maximum temperature of about 720° C. Heat transfer calculations, however, predicted a much faster rise time for the temperature and also a high final temperature. Thus, the heat transfer rate of molten UO_2 to the plate is considerably less than predicted. The following considerations would tend to reduce the calculated heat transfer rate.

1) The UO_2 was not as hot as expected because the UO_2 has been partially reduced in the arc furnace to UO_x where x is less than 2. Analysis of the uranium oxide showed in one case that x is 1.69 and in another 1.4. The melting point of uranium oxide has been investigated by Latta and Fryxell.* For example, UO_x has a solidus of about 2430° C and a liquidus of 2600° C, both considerably below the

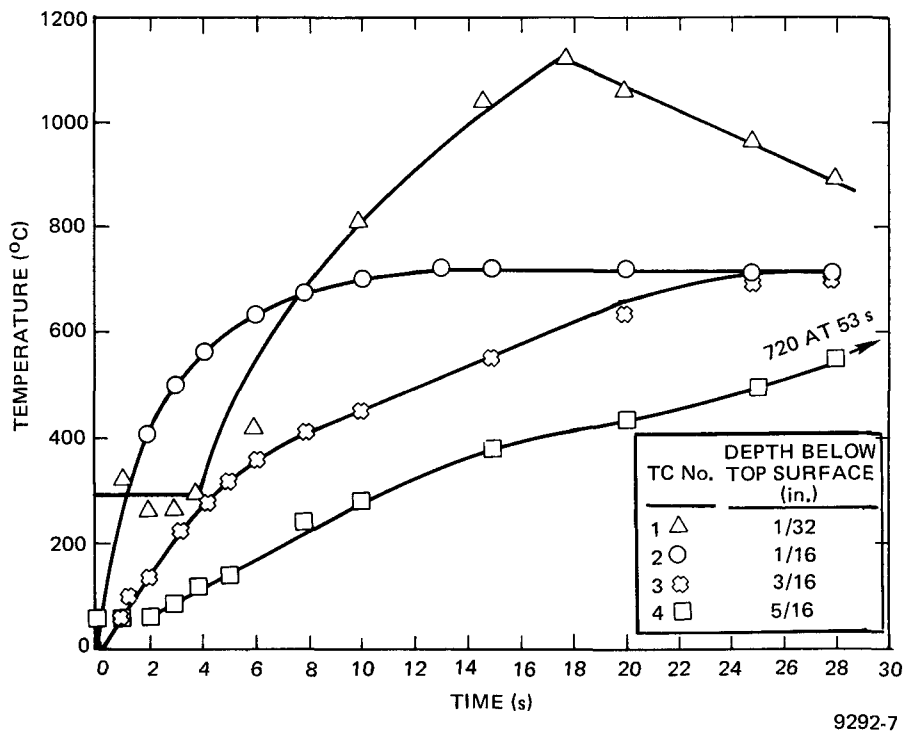

Figure 7. Temperature Rise vs Time Following UO_2 Pour

*R. E. Latta and R. E. Fryxell, "Determination of the Solidus-Liquidus Temperatures in the UO_{2+x} System," Transactions of the American Nuclear Society, 8, 2 (1965)

melting point of 2830° C for pure UO_2. Thus, for pouring, the uranium oxide temperature need only be above the solidus temperature of 2430° C. The UO_x is a better simulant for mixed oxide fuel than pure UO_2 because the mixed oxide has a solidus and liquidus temperature below that of UO_2. The presence of fission products enhances the effect.

2) The uranium oxide does not come into intimate contact with the steel plate, but rather a gas film is formed in spots. The bottom surface of the UO_x after removal from the steel is shown in Figure 8. The rough surface indicates the presence of trapped gas bubbles.

3) The UO_x has reduced thermal conductivity because of the presence of lattice impurities and porosity.

Further, thermal analysis is under way to clarify the processes involved. However, it has been shown that UO_x even in fairly thick layers will not immediately melt the surface of a stainless steel plate.

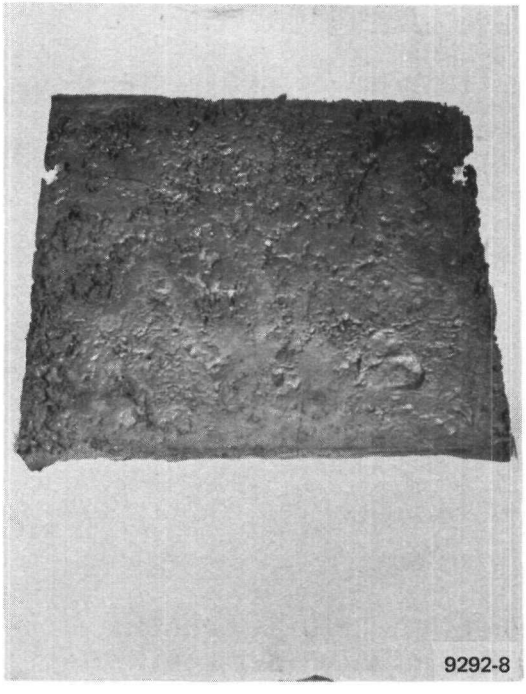

Figure 8. Bottom Surface of UO_2 After Pouring on Steel Plate

C. SUBTASK M – CHARACTERIZATION OF RELEASED SODIUM PARTICLES

A ground-release test releasing sodium combustion products to the environment from an open sodium-pool fire was conducted in cooperation with the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory at their Grid III Meteorological Research Facility located at the Idaho National Engineering Laboratory (Figure 9). This test was run in conjunction with elevated release tests under Task 38, Contract EY-76-C-03-0701.* The test involved releasing 55.3 kg of 540° C sodium from a preheat tank into a 1.1 m^2 burn pan. The sodium was allowed to ignite and burn under natural conditions. The meteorological grid (Figure 10) was instrumented with 50 sampling stations, positioned on arcs 25, 50, 100, 200, 400, and 800 m from the release point. Each sampling station included instruments to determine particle size, concentration, fallout, and chemical species (Figure 11).

The ground-release test (Figure 12) was conducted under Pasquill A meteorological conditions with the wind blowing 8.8 m/s from 220 deg true. The duration of the sodium fire was 60.8 min, and approximately 30% of the combustion products were released and dispersed downwind (Figure 13). The instruments for each arc were simultaneously activated, but each arc was powered in turn so that samples were collected sequentially as the plume swept downwind. Preliminary analysis of the particle fallout collectors indicate that the highest particle fallout occurred near the release point. (A fallout desposition of $\sim 1 \times 10^3$ g/m^2 was observed 1 m downwind.) Fallout deposition diminished from 1 g/m^2 at 25 m to 10^{-3} g/m^2 at 800 m. Analysis of particle size, concentration, and species is in progress.

D. SUBTASK N – RISK ANALYSIS

The first task completed during this period was the identification of the Key LOA-3 and LOA-4 issues, which are related to the AI R&D work. The DOE LOA framework and tentative probability allocations were utilized as the starting point. Probabilistic event trees, of which Figure 14 is an example, in each of the affected LOA-3 and LOA-4 areas were utilized to identify the relative

*Supported by DSE-DOE

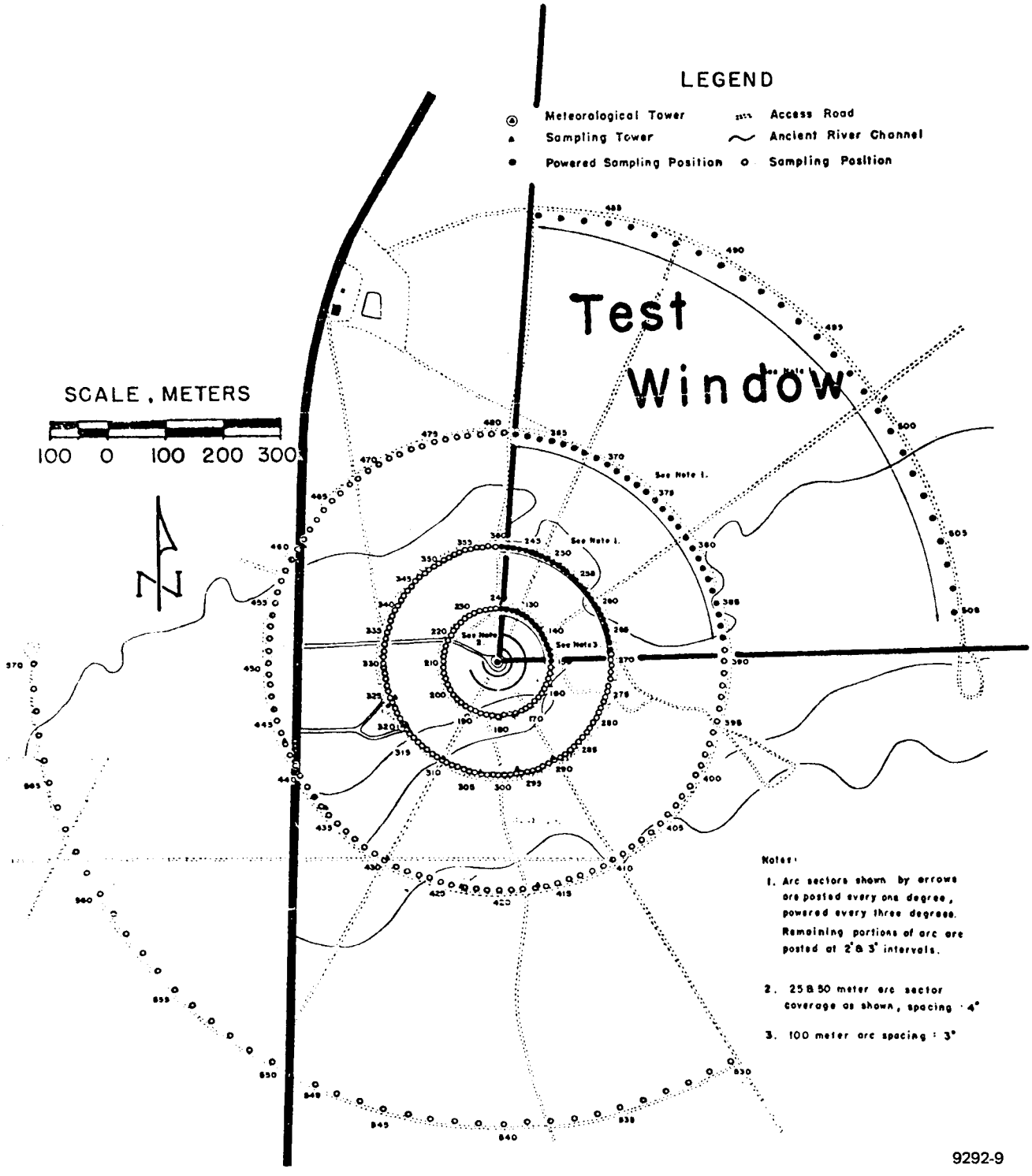

Figure 9. Grid III Research Facility

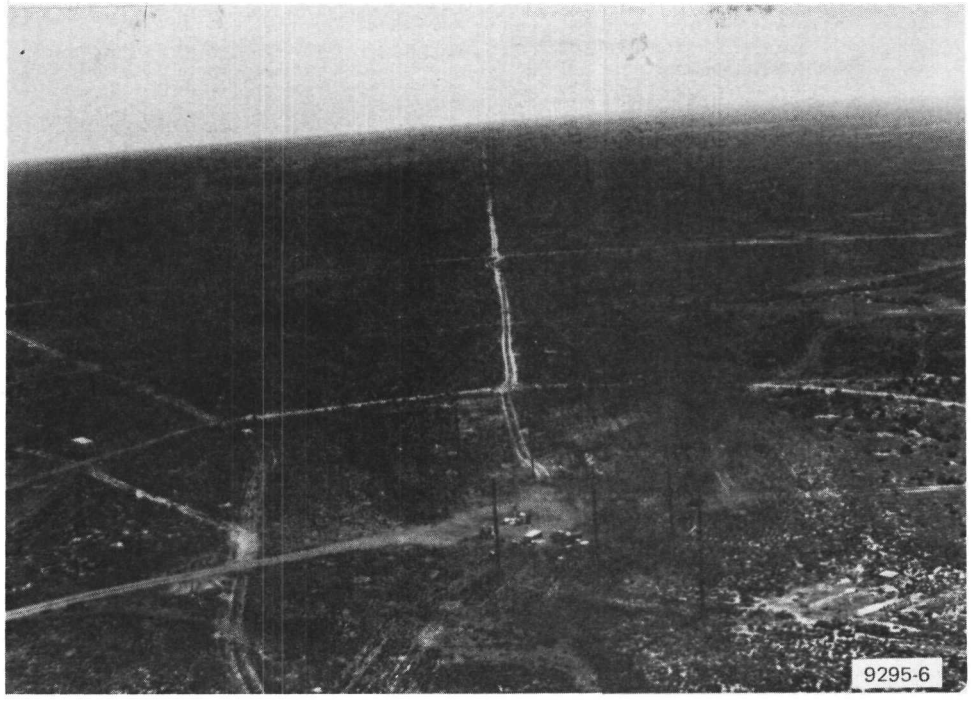

Figure 10. Aerial View of Grid III Research Facility

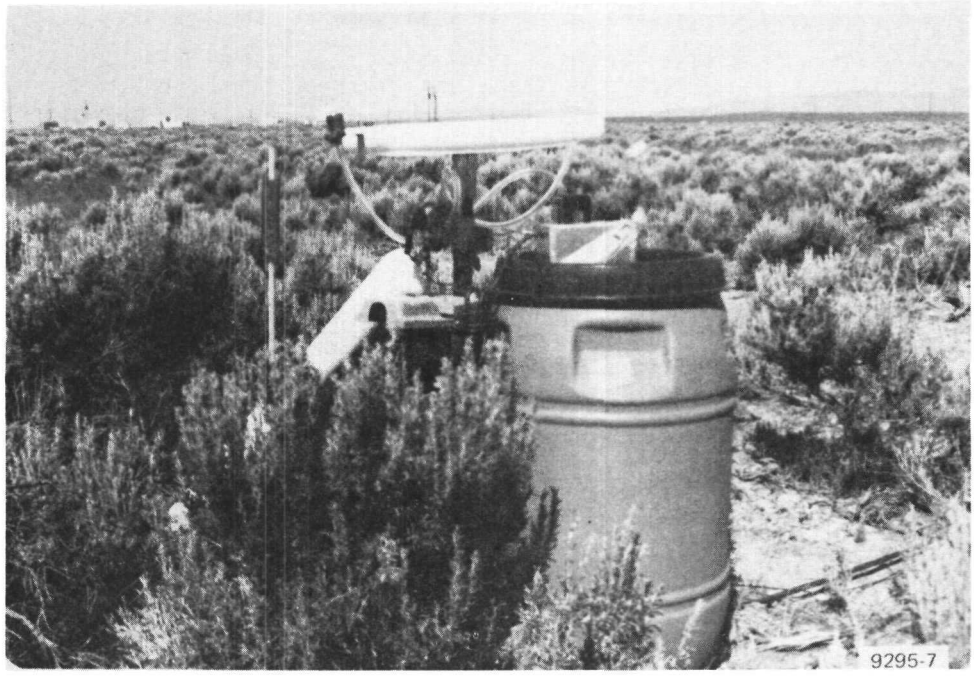

Figure 11. Typical Particle Sampling Station Positioned on Meteorological Grid

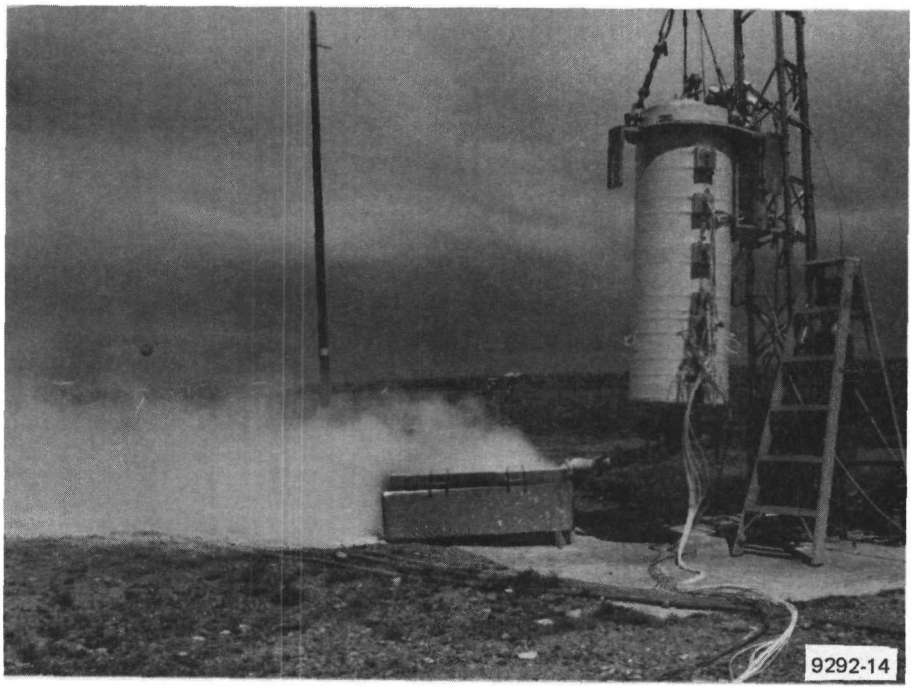

Figure 12. Ground Level Particle Release from Sodium Pool Fire

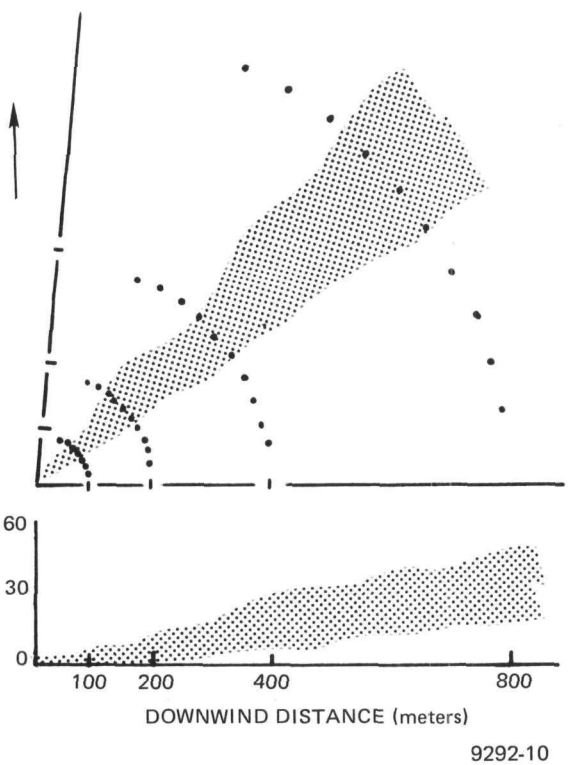

Figure 13. Plan and Axial View of Plume Dispersion

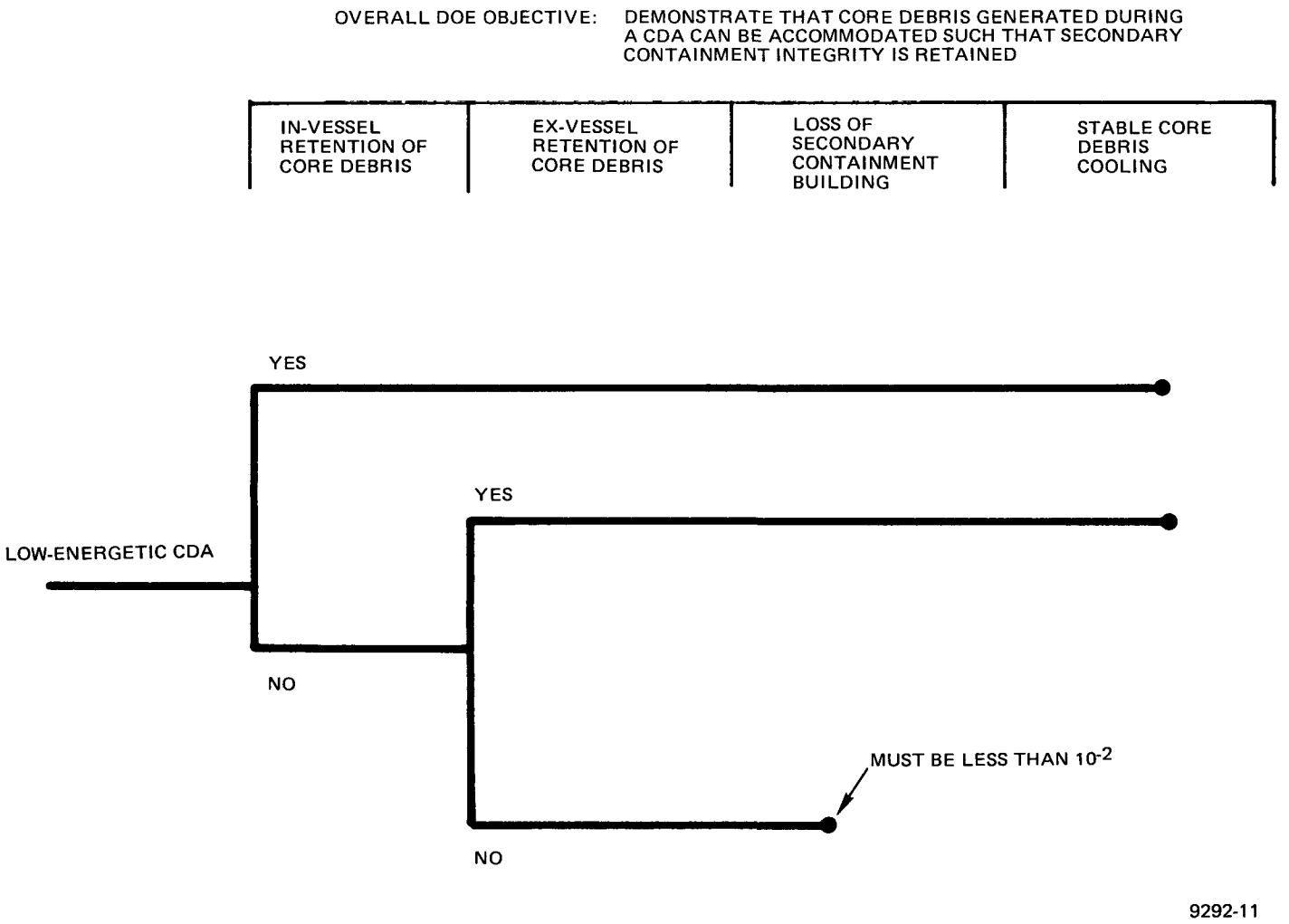

Figure 14. LOA-3 Criteria for R&D Goals – Core Debris Accommodation

role of top-level processes in satisfying the overall LOA probability requirements. The Key LOA-3 and LOA-4 design issues evolve naturally from these event trees.

The second task completed during this period was the identification of the generic relationship of each AI Safety R&D project area to resolution of the issues identified above. In this process, the design options available to resolve each issue were compared with respect to their relative costs, relative design merit, and relative licensing uncertainty. The results were utilized to prioritize, with respect to R&D importance, the technology areas associated with each design option. The AI Safety R&D projects which are applicable to each of these areas were identified and prioritized accordingly. As a result, each AI subtask can now be traced directly to a particular generic technology area(s) and an associated Key LOA-3 and/or LOA-4 safety issue(s).

The next step in the planning effort involves identification of a preliminary work breakdown structure for each of the AI R&D subtasks. The process for achieving this is shown in Figure 15. It is designed to utilize probabilistic methods to define, on an approximate yet consistent quantitative basis, R&D required in each basic phenomenological process identified as important. In this manner, the extent of R&D in each area is appropriately limited and aptly directed. Once identified, these various detail R&D tasks can then be prioritized according to relative cost and benefit to the LMFBR design process.

IV. NEXT REPORT PERIOD ACTIVITIES

Subtask D. Reactor head leak path tests with aerosol mixtures of UO_x + Na will be made. Liquid sodium will be sprayed directly on molten UO_2 within the furnace tank. The resulting aerosol will be a mixture of UO_x + sodium. Fallout and size distribution measurements will be made.

Subtask F. UO_x pouring tests will continue in order to determine heat transfer rates between molten UO_x and underlying materials. A 100-kW inductive heater is being installed in order to heat interacting materials after a pour to simulate the effects of long-term fission product heating.

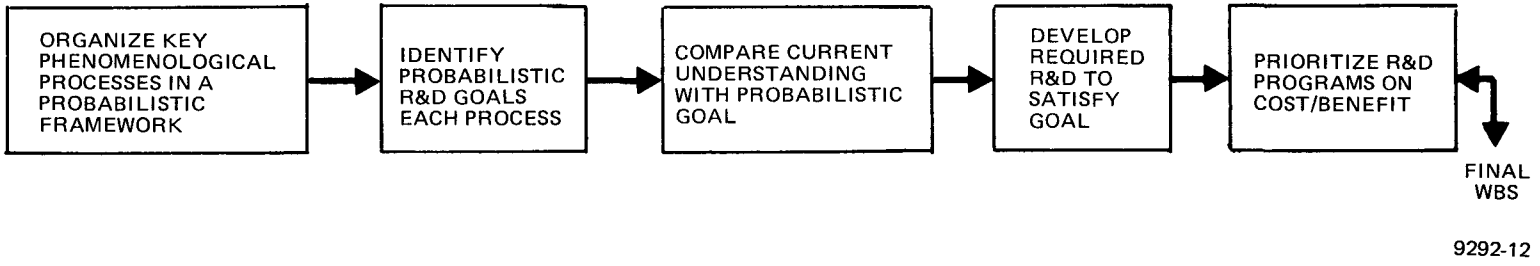

Figure 15. Ongoing Detail R&D WBS Identification Process

Subtask M. Analysis of the ground release test performed in Idaho will continue. Particle size, concentration, and species will be determined for each collection station.

Subtask N. The preliminary work breakdown structure planning effort will be completed. The output is expected to be a program plan, which delineates a proposed R&D activity, the phenomenological area that it addresses, the degree of R&D goal achievement to be met by the proposed activity, and its relationship to the overall LOA-3 and/or LOA-4 program.

The resulting AI Safety R&D program will be adjusted to accommodate the changing needs of the overall LMFBR safety program. Consequently, there will be an ongoing effort to update the AI R&D program by combining the technological results emanating from the entire LMFBR development effort, as illustrated in Figure 16.

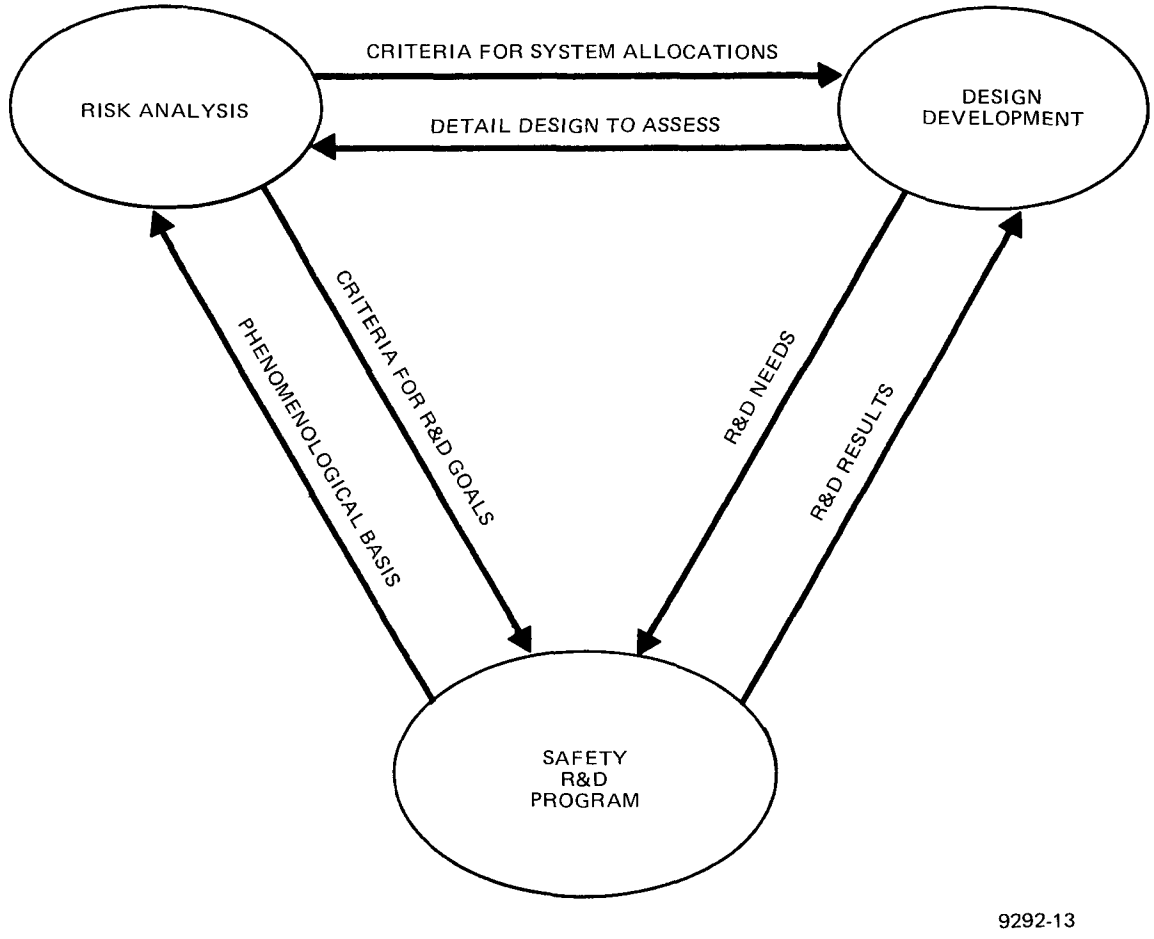

Figure 16. Roll of Risk Analysis and Design Development in Establishment of the LMFBR Safety R&D Program