SESSION X

LMFBR AIR CLEANING SYSTEMS

Wednesday, August 4, 1976
CHAIRMAN: C. Newton

THE AEROSOL BEHAVIOR IN LMFBR ACCIDENTS: RESULTS OF TUNA EXPERIMENTAL PROGRAM AND COMPARISON WITH PARDISEKO CODE
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EVAULATION OF IN-VESSEL AIR CLEANING SYSTEMS FOR AN LMFBR
W. C. Hinds, E. F. Mallove,
M. W. First

OPENING REMARKS OF SESSION CHAIRMAN:

As you know, air cleaning systems have long been an important safety feature in nuclear installations and are often provided for lightwater reactors as a means of reducing radiological consequences of postulated accidents.

You may be wondering why we have a separate session on LMFBR air cleaning. The reason, quite simply, is that postulated accidents for LMFBR's and the environments that they lead to are significantly different than those postulated for lightwater reactors.

The main difference, of course, is the sodium coolant which does lead to a potential for large releases of sodium oxide and sodium hydroxide aerosols. Such aerosols do provide quite a challenge for an air cleaning system. Early research indicated that HEPA filters rapidly plugged when challenged with sodium oxide and sodium hydroxide aerosols. Therefore, if one is to use some sort of a filtration system, a prefilter would be necessary.

The work to data on prefilters is very encouraging and a number of options appear to be viable. Spray systems, which are sometimes used in light water reactors, are also a candidate for LMFBR air cleaning systems. We cannot, of course, use water because of its incompatibility with sodium, but other materials are under investigation and show promise.

A point I would like to leave with you is that ERDA is agressively pursuing the development of air cleaning systems as an engineered safety feature for LMFBR's.

THE AEROSOL BEHAVIOR IN LMFBR ACCIDENTS: RESULTS OF TUNA EXPERIMENTAL PROGRAM AND COMPARISON WITH PARDISEKO CODE

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Abstract

Aerosol behavior in contained vessels is of high significance for LMFBR safety analysis. In the TUNA program UO_2-particle concentrations have been measured in a 2.2 m^3 and a 0.022 m^3 vessel as function of time. A corresponding computer code PARDISEO III was developped which is capable to describe the concentration time function for different geometries and gas temperatures. The aerosol processes most important for aerosol behavior have been identified. The significant experimental results are reported and compared with theory. Open problems in the complete description of aerosol behavior in LMFBR containments are discussed.

I. Introduction

The activity release and transport into the environment in the case of a severe accident in a nuclear power plant is of high significance in any reactor safety analysis. For the LMFBR the special problems of formation, transport, behavior and (eventually) release to the environment of aerosols originated from core disassembly and other sources are of particular interest.

In the Nuclear Research Center Karlsruhe a research program has been carried out which dealt with the behavior of nuclear aerosols in contained systems. The program has been completed in 1974 with his first phase and covered the investigation of the time functions of UO_2 aerosol concentration in dry and N_2 filled atmosphere, the determination of the aerosol processes involved and the modelling of the airborne aerosol system by computer code.

This paper describes the more important experiments, their results, the general findings on aerosol processes, the computer code developped and the still existing problems.

II. Experiments on Nuclear Aerosols

Goals

The goals of the program were the following:

- Determination of the particle size and related parameters of nuclear aerosols (i.e. aerosols formed in typical accidents in LMFBR's with core disassembly) as function of accident conditions
- Determination of the particle number concentration and aerosol mass concentration as function of time in the containment system considered
- Determination of physical and chemical properties of nuclear aerosols, their

interaction processes and the influence of these processes on the aerosol behavior

- Development of suitable models capable to extrapolate of the experimental results to real containment geometries.

The ultimate goal of the program is the reliable description of the activity release in severe accidents of a LMFBR.

Experimental Results

The experiments have been carried out in the experimental facility TUNA (Teststand für die Untersuchung nuklearer Aerosole) which has been described elsewhere(1) in detail. In this facility a number of aerosol measurement techniques are concentrated around a stainless steel vessel of 2,2 m^3 free volume simulating a nuclear reactor containment. The main characteristics of TUNA are given in table 1, a schematic graph is given in figure 1.

The UO_2-aerosols investigated in this part of the experimental program were produced in all cases by the exploding wire technique. A sintered UO_2 cylinder of 40 mm length and 4 mm diameter is preheated by an irradiation furnace until it becomes electrically conductive. Then a puls current from a bank of capacitors is lead through the cylinder, heating it up and vaporizing parts of the material. A rather fine aerosol is produced by this way as has been reported in (2). The typical conditions under which the UO_2-aerosol have been formed in all experiments are given in table 2.

Typical aerosol measurement methods were used,namely for the particle number concentration the condensation nuclei counter, for aerosol mass concentration the activation analysis, for particle size analysis the usual electron or light microscope techniques.

Because of the necessity of modelling the aerosol behavior for extrapolation to real containment conditions the exact description of the particle number concentration as function of time is the most important part of the program. Determining the particle number concentration the following test runs have been carried out (the most important ones are mentioned only):

- Vaporization of UO_2 in N_2 in the main vessel of TUNA and subsequent measurement of particle number concentration as function of time at room temperature

- Vaporization of UO_2 in N_2 in the small adjacent vessel (aerosol chamber) and subsequent measurement of particle number concentration as function of time at room temperature

- Vaporization of UO_2 in N_2 in the main vessel and subsequent measurement of particle number concentration at function of time for different gas temperatures.

The results of these tests are summarized in figure 2,3 and 4. The range between the solid lines (fig. 2) represents the error range. All experimental measuring points (11 tests) were within that range of error.

main vessel	material	stainless steel
	volume (cylindrical)	2.22 m^3
	surface	8.8 m^2
	hight	2.9 m
	diameter	1.0 m
	distance from probe to bottom	3.1 m
aerosol chamber	(on top of the vessel)	
	material	stainless steel
	volume (cylindrical)	0.02 m^3
	surface	0.5 m^2
	hight	0.34 m
	diameter	0.30 m
	distance from probe to bottom	0.17 m

Table 1 Data of TUNA

probe (cylindrical)	UO_2 sintered
dimensions	
length	40 mm
diameter	4 mm
electrical energy inserted	ca. 500 Wsec/g
energy insertion time*)	ca. 3 msec (0.1 msec)
vessel conditions	
pressure	1 at
temperature	20 °C
relative humidity	10 %
atmosphere	N_2 filtered
purity of the UO_2 aerosol	
impurities (total)	< 0.1 %
impurities elements	Ta.W.Ni.Mn.

*) Experiments No. 147 and 166 have been carried out with time constants of 0.1 msec, experiments No. 152 and 163 with time constants of 3 msec. An influence of time constants on the primary particle behavior has not been observed.

Table 2 Conditions of aerosol formation in TUNA

An important characteristic of aerosol behavior in closed systems is the initial particle size distribution. Extensive measurements of these parameters revealed the following result:

- The initial particle size distribution is logarithmic normal but does not necessarily remain exact log-normal during the whole course of the life of the aerosol system

- The initial mean geometric diameter (projected area) depends on the energy inserted into the UO_2 probe. For 500 Ws/g the MGD was 0.08 µm with $\sigma = 1.85$. Higher inserted specific energy resulted in smaller particle size.

Discussion of Experimental Results and Comparison with Theory

Early presumptions upon the most important aerosol processes acting in an airborne, dry and contained aerosol system resulted on the basis of general considerations of aerosol physics in the statement, that at least the agglomeration process (coagulation) and the settling process (sedimentation) are effective(3). As can be seen from fig. 4 the effect of temperature on the aerosol concentration decay curve is significant also. Therefore, thermophoresis (aerosol transport in a temperature gradient) contributes also and has to be incorporated in the modelling. Furthermore, the diffusion process which takes into account the fact that along the containment wall will always exist a concentration gradient has to be taken into account.

More or less (depending on containment geometry , particle concentration, gas temperature and other parameters) all four processes are effective. The computer code PARDISEKO III, developped on the basis of the TUNA experimental program results, includes all these aerosol processes in an adequate form(4). The essential mathematical equations of PARDISEKO III are listed in the appendix of this paper.

In the comparison of experimental and theoretical (PARDISEKO III) results it was found that an aerosol model comprising the above mentioned aerosol processes can describe the aerosol behavior satisfactory if essentially the following aerosol related parameters are known (see appendix):

$c_p(0)$ = initial particle number concentration
r_g = initial mean geometrical particle radius
σ = standard deviation of radius distribution
δ_D = mean diffusion boundary layer thickness
δ_T = mean thermal boundary layer thickness
f = collision form factor
κ = dynamic form factor
ρ = density of particle material

Along with these aerosol parameters, of course, a number of non-aerosol parameters (gas viscosity, gas and wall temperatures, containment geometry, thermal conductivity of carrier gas and others) must be known. However, these parameters are easy to determine or to measure. From the aerosol parameters the first three ($c_p(0)$, r_g, σ) were measured in the experimental program. δ_D and δ_T were estimated from literature data (see(1)), where f and κ were used as fitting parameters.

These two form factors describing the deviation from behavior of a spherical particle in comparison to the real irregularly shaped particle related to the aerosol process considered (f = collision form factor relates to coagulation, κ = dynamic form factor relates to diffusion, sedimentation and thermophoresis) appeared to be the focal point in the aerosol modelling theory.

κ has been measured by other authors for a variety of particles of different material except UO_2, whereas f can only be determined indirectly. Using $\kappa = 3.5$ according to literature data for other particles (here κ lies between 2 and 6) and assuming f = 8.2 a time function for $c_p(t)$ was calculated with PARDISEKO showing good agreement between experiment and theory (fig. 2, curve I). For comparison κ and f were varied (see fig. 2). Curve II is based on f = 1.0 and κ = 1.0 which means spherical particles only. Curve III is based on f = 1.0 and κ = 3.5 and curve IV on $f = 8.2$ and $\kappa = 1.0$.

A further prove of the assumed values for f and κ can be taken from fig. 4. Here PARDISEKO was applied to an aerosol system at elevated temperatures. Again, with the same form factors as used in curve I of fig. 2 the best agreement between experiment and theory was achieved. Moreover, for the case of the small chamber experiments (fig. 3) again the applied κ and f values as in curve I of fig. 2 gave the best agreement.

It should be mentioned, however, that in all PARDISEKO calculations the theoretical density of the particle material was assumed. This is not in agreement with the experimental findings, since all UO_2 particles investigated showed a more porous structure than a compact structure. There exists, however, certainly a close correlation between particle form factors and particle density. Therefore, a combination of ρ with κ and f will probably be a better approach from the standpoint of aerosol physics. Nevertheless the form factors discussed are of great importance in aerosol modelling and cannot be neglected if the behavior of irregularly shaped particles is described.

III. On the State of the Art of Aerosol Modelling

In the foregoing chapters the TUNA program results in comparison with PARDISEKO theory was discussed. Concerning the behavior of nuclear aerosols in a LMFBR post-accident atmosphere the present state of knowledge can be described as follows:

a) The time function of an instantaneously formed aerosol concentration in a contained system can be satisfactorily described by the PARDISEKO III code, if some assumptions (form factors) are made which from the standpoint of aerosol physics are reasonable.

b) In the accident analysis not only UO_2 (or PuO_2) aerosols are important. For the SNR-300 four aerosol sources are considered (see table 3). Only two of them are instantaneously formed. Although PARDISEKO III is capable of calculating several timely overlapping sources the confirmation by experiments is still lacking.

c) Since the aerosol system in a core disassembly accident is formed of several sources the problem of mixed aerosols (consisting of UO_2, Na, fission products etc.) should be investigated. The properties (physical, chemical) of these aerosol sources should be investigated.

d) In all so far known experiments on aerosol behavior in contained systems only small volumes have been used (up to 10 m^3). In that volumina the influence of thermal convections is small and negligible. The effect of thermal convections in real containments on aerosol concentration time functions remains to be investigated.

e) In the post-accident containment atmosphere of LMFBR's a considerable amount of vaporized sodium will exist. Since depending on temperature and pressure conditions some of the sodium will condense the influence of condensation on particle behavior should be investigated.

IV. Summary

The TUNA program on the behavior of nuclear aerosols in contained systems has

SOURCE ORIGIN	COMPOSITION	TIME OF FORMATION	INITIAL PARTICLE DIAMETER	REMARKS
CORE DISASSEMBLY	UO_2-PuO_2, FISSION PRODUCTS STEEL, SODIUM	INSTANTANEOUS	< 0.08 µm (INCREASING)	HIGH INITIAL CONCENTRATION
NA-RESIDUAL O_2 REACTION	Na_2O	INSTANTANEOUS	0.1 µm (INCREASING TO CA. 0.4 µm)	
NA-EVAPORATION FROM CORE CATCHER	NA	LONG TERM (DAYS)	0.1 µm (INCREASING TO CA. 0.3 µm)	RECONDENSATION AEROSOL WITH TRACE FISSION PRODUCTS AND FUEL
H_2O-EVAPORATION FROM CONCRETE	NAOH	LONG TERM (DAYS)	?	
GFK/LAF I	AEROSOL SOURCES IN ACCIDENT OF LMFBR			33346

table 3

been carried out in his first phase by using inert UO_2 aerosols in an inert N_2 atmosphere. These experiments which did not yet simulate real containment conditions served to explore what aerosol processes are involved in aerosol behavior. The results show that the most important aerosol processes are

- coagulation
- sedimentation
- thermophoresis and
- diffusion

In modelling aerosol behavior it has been clarified that certain aerosol parameters (form factors) play an important role and cannot be neglected. The computer code PARDISEKO III describes satisfactorily the experimental results and is a tool in the calculation of activity release in heavy accidents. Further research is necessary concerning the influence of thermal convection and condensation as well as of the properties of mixed aerosols.

Acknowledgement

In the course of the TUNA program a number of colleagues in the Laboratory of Aerosol-Physics and Filter-Technology in the Nuclear Research Center Karlsruhe have contributed to the experimental and theoretical results. In particular the work of H. Wild and H. Jordan is greatly appreciated.

Appendix

Model equations of PARDISEKO III according to(4)

$$\frac{\partial n(r_e,t)}{\partial t} = S(r_e,t) - (\alpha_D(r_e) + \alpha_S(r_e) + \alpha_T(r_e) + \alpha_L(r_e))\, n(r_e,t)$$

$$+ \int_0^{r_e/\sqrt[3]{2}} K(\sqrt[3]{r_e^3 - {r'_e}^3}, r'_e)\, n(\sqrt[3]{r_e^3 - {r'_e}^3}, t)\, n(r'_e,t)\, \frac{r_e^2\, dr'_e}{(r_e^3 - {r'_e}^3)^{2/3}}$$

$$- n(r_e,t) \int_0^{\infty} K(r_e,r'_e)\, n(r'_e,t)\, dr'_e$$

n = Particle size distribution

r_e = Mass equivalent radius

S = Source function

$\alpha_D = \frac{kTB(r_e)}{\delta_D} \cdot \frac{A_D}{V}$ = Deposition rate coefficient due to diffusion

$\alpha_S = \frac{4\pi}{3} r_e^3 \rho g B(r_e) \frac{A_S}{V}$ = Deposition rate coefficient due to sedimentation

$\alpha_T = \frac{9\pi\eta^2 r_e}{\rho g} \left(\frac{1}{1+3Kn}\right)\left(\frac{k_g/k_s+2.48Kn}{1+2k_g/k_s+4.96Kn}\right)\frac{T-T_W}{T}\, \frac{B(r_e)}{\delta_T}\, \frac{A_T}{V}$

= Deposition rate coefficient due to thermophoresis

α_L = Leak rate coefficient

$K = 4\pi kTf(B(r_e) + B(r'_e))(r_e+r'_e) + \varepsilon(r_e,r'_e)\frac{4\pi}{3}\rho g f^2 \cdot \left| r_e^3(B(r_e) - {r'_e}^3 B(r'_e)) \right| \cdot (r_e+r'_e)^2$

= Coagulation function

$B = \frac{1}{\kappa 6\pi\eta r_e}(1+AKn+QKnC^{-b/Kn})$ = Mobility

$$C_T(t) = \int_0^\infty n(r_e,t)dt = \text{Particle number concentration}$$

$$C_M(t) = \int_0^\infty \frac{4\pi}{3} \rho r_e^3 \, n(r_e,t)dr_e = \text{Aerosol mass concentration}$$

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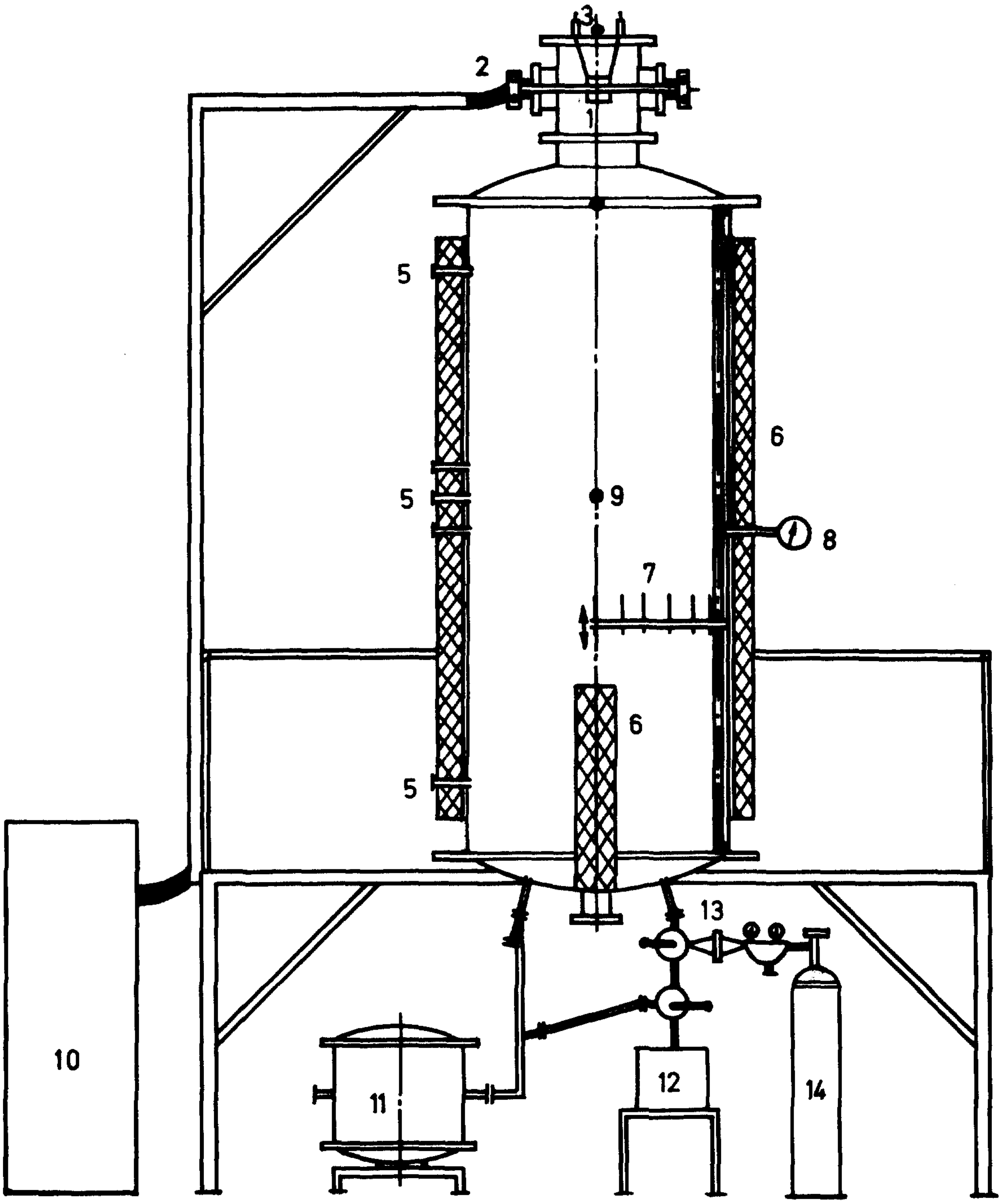

1 aerosol chamber
2 coaxial cable
3 preheater electrical penetration
4 TUNA main vessel
5 aerosol measuring ports
6 gas heater (internal , external)
7 thermocouple rig
8 manometer
9 pressure transducer
10 power supply and condenser bank
11 off-gas filter
12 pump
13 inlet filter
14 gas supply

Figure 1 TUNA , schematic

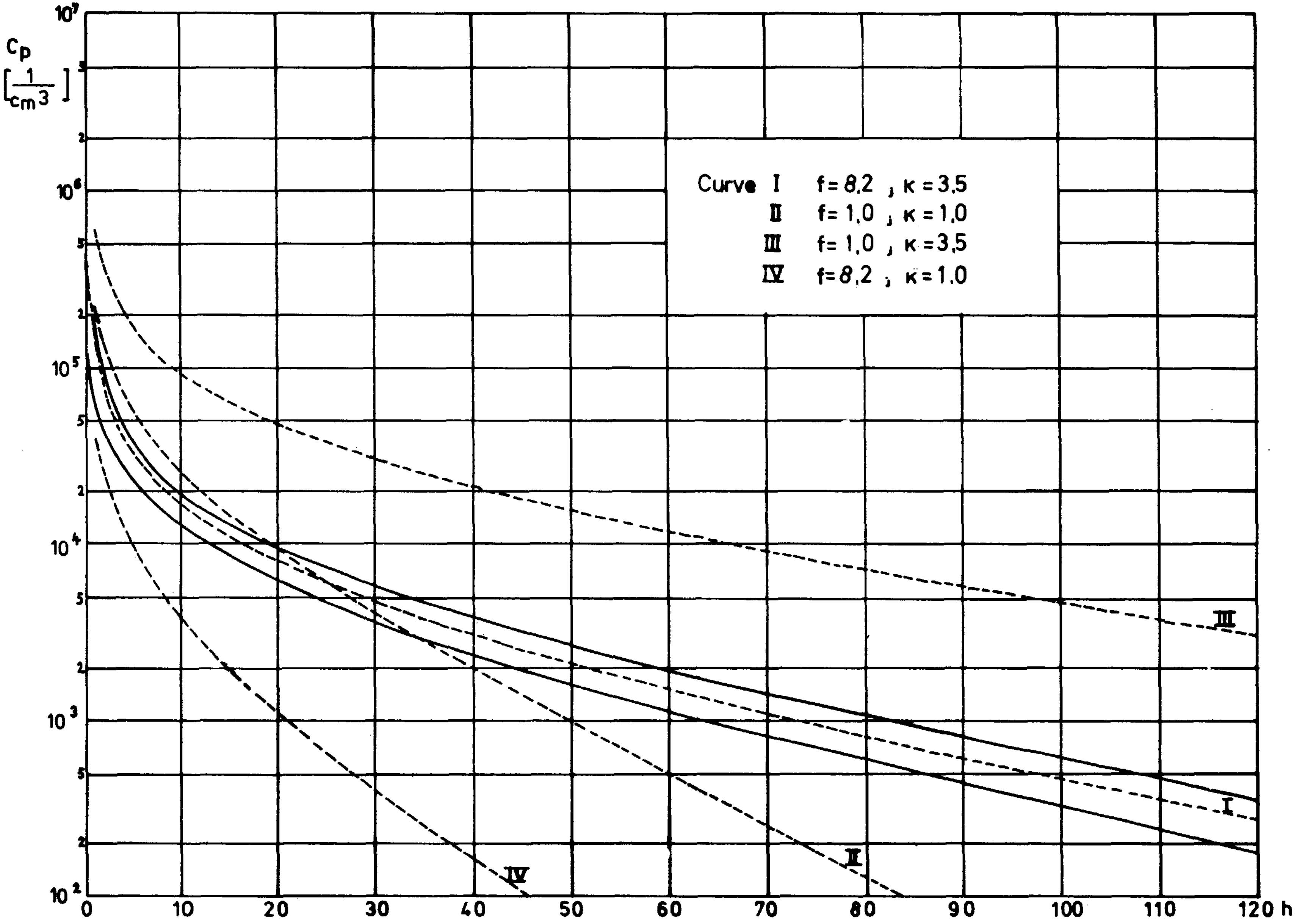

Figure 2 Comparison Experiment - Theory (TUNA vessel) UO_2 particle number concentration as function of time at room temperature

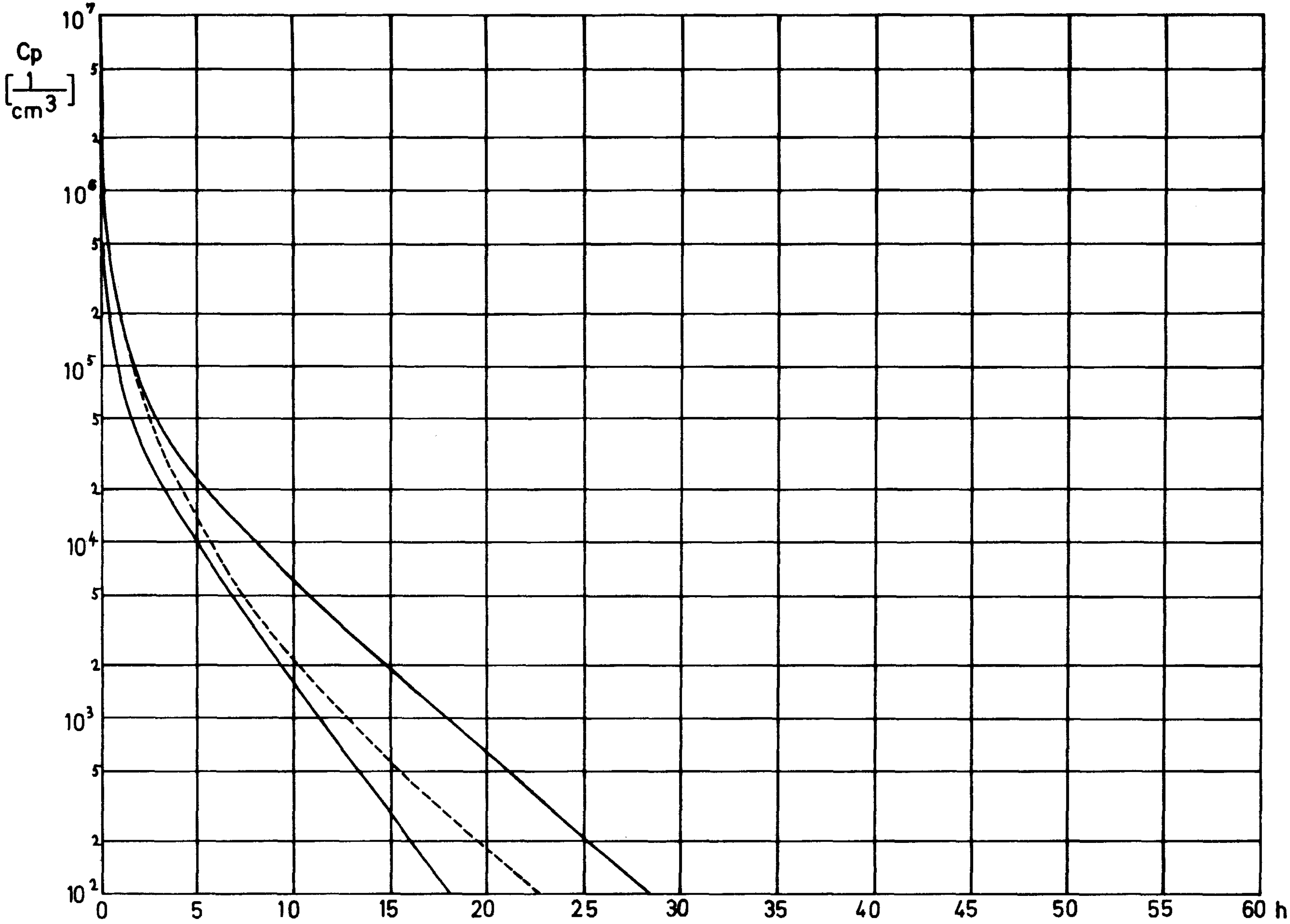

Figure3 Comparison Experiment-Theory (aerosol chamber) UO_2 particle number concentration as function of time at room temperature

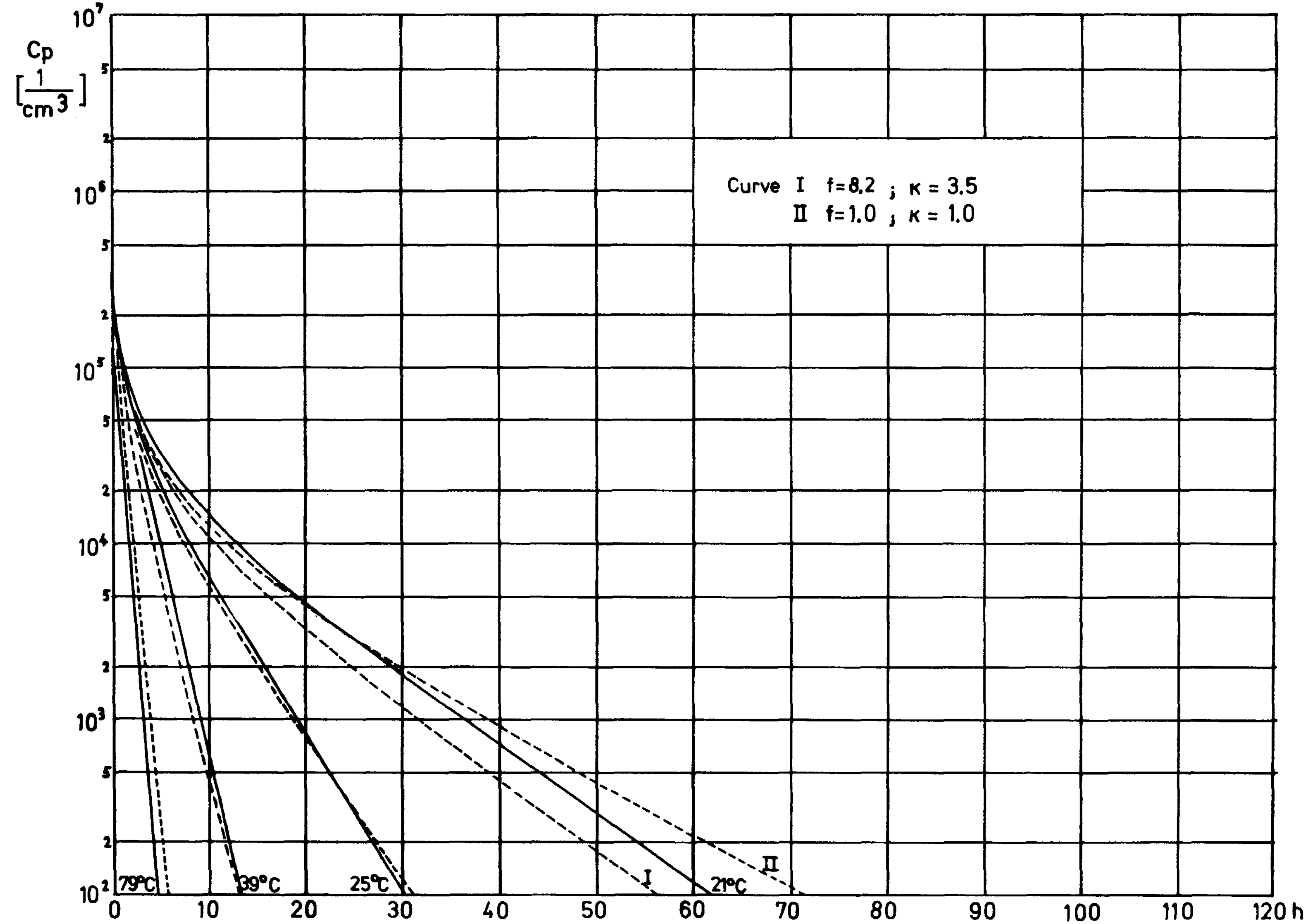

Figure 4 Comparison Experiment - Theory (TUNA vessel) UO_2 particle number concentration as function of time at different gas temperatures

DISCUSSION

NEWTON: I personally consider this paper on aerosol behavior very important for a number of reasons. For one thing, it is a natural attenuation mechanism which, if we understand if sufficiently well, gives us a great deal of attenuation credit. Also, it permits an assessment of the real benefits of air cleaning systems to be evaluated. That is, one can compare what the radiological doses will be with and without an air cleaning system. Finally, of course, by understanding the aerosols generated from these accidents better, we're able to characterize the aerosol that challenges the air cleaning system that we're trying to design.

AN EVALUATION OF ALTERNATIVE AIR CLEANING SYSTEMS FOR EMERGENCY USE IN LMFBR PLANTS

(USERDA Contract AT(4501)-2170)

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Abstract

Twenty-four air cleaning systems, with widely differing air cleaning techniques, are evaluated for feasibility as engineered safety features in LMFBR plants. System designs are considered for both containment and containment/confinement type plants. A source term for release from the reactor vessel is postulated. The systems are designed to provide a 2-hr dose reduction factor of 10 or an overall decontamination factor of 100 for containment and containment/confinement uses, respectively. Each air cleaning system is evaluated against criteria developed for this purpose, the merits and weaknesses are discussed, and development needs are outlined. For single containment systems, a recirculating-prefilter/HEPA-filter system is shown to be useful with minimal development needed to substantiate the design assumptions. In-vessel acoustic aerosol agglomeration offers attractive potential but requires considerably more development. For containment/confinement use, a sand bed filter with HEPA and charcoal backup can accommodate a sodium fire in the confinement building, as well as the postulated radiological source term. The need for development of a high-capacity, low-efficiency sand bed filter is suggested.

I. Introduction

Air cleaning systems are used extensively in existing nuclear facilities for controlling normal plant effluents and for mitigating the radiological consequences of postulated major accidents. The systems can be divided into three categories: containment atmosphere cleanup systems, ventilation exhaust systems, and process off-gas systems. Systems with similar functions for use in Liquid Metal Fast Breeder Reactors (LMFBRs) are in a developing stage and for application to postulated major accidents will require significant modification and development before their practicability can be demonstrated.

The feature of an LMFBR which has the largest impact on air cleaning for accident mitigation purposes is the use of sodium as the coolant. Although each reactor must be evaluated on an individual basis, radiological analyses of site boundary doses for postulated severe accidents in LMFBRs show that inhalation of aerosol particles containing plutonium may be a concern rather than thyroid dose from radioiodine, as is the case in light water reactors (LWRs).(1) Thus, aerosol attenuation is the highest priority for LMFBR emergency air cleaning systems (EACSs). A second feature of an LMFBR which strongly affects the design requirements for an EACS is the release of sodium during the postulated accident, with its attendant high aerosol mass concentration and chemical reactivity considerations.

The purpose of the work reported in this conference was to evaluate all air cleaning concepts which appeared to have merit for use as accident consequence mitigating systems in LMFBR plants and to recommend the systems which have the greatest potential for development into practical engineered safety systems. Realization of this end goal would provide the designers of future commercial LMFBRs with a valuable option in designing containment systems to meet regulatory guidelines. The Nuclear Regulatory Commission (NRC) has expressed confidence in the reliability of air cleaning systems to perform their intended function in LWR plants.(2) Although the dose reduction factor (DRF) attainable by an EACS is smaller than some of the attenuation processes which can be postulated,(1) the probability of attaining the design DRF is essentially unity. This provides added incentive to develop a suitable EACS for future LMFBR plants.

The work reported here included the definition of reference plant (1000 MW_e) features important to the EACS design, selection of an EACS design basis source term, definition of criteria for rating the various EACS candidates, making rudimentary conceptual designs of twenty-four candidate EACSs, evaluating the candidates against the criteria and ranking them against each other, and finally, selection of the systems which appear most promising for development.

II. Definition of Reference Containment Designs

Discussion

The ambient conditions and operational requirements for an emergency air cleaning system depend strongly on the type of containment system provided for the reactor plant. Thus, the selection and description of the plant containment features is a prerequisite step before an evaluation of air cleaning systems can be made. A review of existing LMFBR plant containment designs revealed that no one type of containment system can be designated as being standard for future large LMFBR plants.(3-6) For the purpose of this study, several reference designs were selected to provide a basis for establishing EACS design and operating conditions and requirements.

The three containment types summarized in Table 1 were selected for the present EACS study. Each of these three designs imposes significantly different requirements on an EACS, and each appears to offer an economically viable option to future reactor designers. The reactor is the same for each of the three reference plants: 1000 MW_e, 2430 MW_{th}, 15,300-kg heavy metal oxide (13,500 kg as heavy metal), and fuel material is 25 percent PuO_2, 75 percent UO_2.

Single Containment Design

The single containment design is physically similar to the FFTF with the open head compartment option. It is also similar to the containment system provided for the British DRF.

At the present time, the type and size of future EACSs is unknown. For purposes of this study, an air cleaning system working on air in the containment vessel, with an effective removal rate (λ) of 5 hr^{-1}, was assumed. The system could be located either entirely

TABLE 1

SUMMARY OF REFERENCE CONTAINMENT DESIGN PARAMETERS

Parameter	Case I	Case II	Case III
Type of Containment	Single Containment	Double Containment	Containment-Confinement
Brief description	Single, low-leakage, cylindrical steel shell surrounding all primary sodium systems.	Sealed, inerted, high-pressure inner containment surrounding reactor vessel and head compartments. An outer low-leakage cylindrical steel shell surrounds the inner compartment.	Sealed, inerted, high-pressure inner containment surrounding reactor vessel and head compartments. A ventilated rectangular building surrounds the inner containments.
Inner containment			
Atmosphere	N/A	99% N_2/1% O_2	99% N_2/1% O_2
Size	N/A	40' D x 50' H, hemispherical top	40' D x 50' H (12.2 m x 15.2 m) hemispherical top
Volume, $ft^3(m^3)$	N/A	29,300 (830)	29,300 (830)
Leak rate, %/day	N/A	100	100
Outer containment			
Atmosphere	Air	Air	Air
Size above operating floor	160' D x 60' straight cylinder with hemispherical top	160' D x 60' (48.8m x 18.3m) straight cylinder with hemispherical top	105' x 204' x 105' (32.0 m x 62.2 m x 32.0 m)
Volume, $ft^3(m^3)$	2.25 x 10^6 (63700)	2.25 x 10^6 (63700)	2.25 x 10^6 (63700)
Leak rate, %/day	0.1	0.1	15,000 CFM (ventilation) (7.1 m^3/s)

internal to the containment vessel or in an external loop. This system could be either a recirculation type (e.g., filters) or a direct application system (e.g., sprays). The design DRF for two hours resulting from operation of this system is ten. For longer periods of time, the DRF would be greater than ten.

Double Containment Design

The principal physical difference between single and double containment schemes is the addition of a sealed dome over the reactor head compartment. The outer containment vessel was taken to be identical with that provided for the single containment case.

The physical size of the inner containment dome was selected as a hemisphere large enough to cover the reactor head compartment. This dome would be removed during refueling operations.

The double containment design is similar in concept to the CRBR design, based on the inerted closed head option, and to FERMI. It is similar to SEFOR which used 10 psi inerted primary vaults as well as an outer steel containment vessel. This design is also conceptually similar to the design proposed for 1000 MW_e by AI.(5) Of these previous designs, only the AI conceptual design included an emergency air cleaning system.

The assumed air cleaning system is one which cleans the air in the outer containment atmosphere with an effective λ of 2 hr^{-1}. This system gives a smaller dose reduction factor than the EACS used for the single containment case, and will treat much less concentrated aerosols because the primary volume allows appreciably more settling and plating than would occur in a single containment. An alternate air cleaning approach would be to clean the gas enclosed in the primary volume.

Containment/Confinement Design

The containment/confinement design is, in effect, a double containment scheme in which the outer barrier is a ventilated building rather than a low-leakage containment shell. The outer building is maintained at a slightly negative pressure by an exhaust system which discharges air through suitable cleanup devices to a stack so that radioactive materials leaked from the primary containment are removed by filters or scrubbers. The containment/confinement concept trades a high leakage rate of processed air (filtered, elevated release) for a low leakage rate of unprocessed air.

The physical size and features of the primary containment volume were assumed to be identical to the double containment plant. The outer confinement building size and the capacity of the EACS were taken from the General Electric 1000 MW_e follow-on study.(6) The design is similar in appearance to several existing designs. The British PFR uses an inner containment scheme with an outer steel structural building. An important difference is that PFR uses a recirculating air cleaning system rather than a single pass system.

Although the specific kind of air cleaner (filter, scrubber, etc.) need not be specified, the total flow rate is specified as 15,000 CFM (7.1 m^3/s). The efficiency required for this system must be high compared to the systems chosen for containment plants. Based on preliminary analyses, it appears that the EACS system will have to achieve a decontamination factor of about 100 or more to give bone doses equivalent to that of a double containment plant.

III. EACS Design Basis Source Term

Basis for Selection of Design Basis Source Term

Definition of the design basis source term (DBST) for the air cleaning study provides a means for evaluating the conditions imposed upon, and performance of, containment systems incorporating an EACS. In selecting the DBST for this study, emphasis was placed on the quantities and type of radioactive materials and sodium which could become airborne, and therefore represent an air cleaning requirement.

A hypothetical core disruptive accident (HCDA) appears to be the most severe type of accident which can be postulated for evaluating containment system performance. ERDA is currently supporting a major analytical and experimental program to develop a source term model describing the release of fuel and fission products from the core to the cover gas and then from the reactor vessel to the head compartment.(7) At the present time, such a model is not completely available and releases postulated in this report are based on parametric studies, judgment, and precedent.

Additional interactions associated with postulated post-HCDA melt-through of the reactor vessel were not assumed to add to the initial short-term releases.

Aerosol Source Terms

The phrase "source term," as used in this paper, refers to the release of materials from the primary reactor vessel to the next level of containment. For the single containment plant, the release is directly into the outer, air-filled containment building via the open head compartment. For both the double containment and containment/confinement plants, the release is into an inerted inner containment volume.

The mass releases of radioactive materials and sodium from the reactor vessel are summarized in Table 2. The aerosol properties were developed by using HAA-3b code(8) calculations.

Comparison of Containment Concepts

An evaluation of various containment concepts is beyond the scope of the present study. However, the analyses performed here provide some bases for a general comparison. It must be strongly emphasized, however, that variations in each of the reference plant designs could greatly alter the conclusions.

Table 3 is a compilation of data selected from the previous sections of this report for total mass and plutonium leaked to the

TABLE 2
ASSUMED INSTANTANEOUS AEROSOL SOURCE

Parameter	Release Directly to Containment Building	Release to Sealed Primary Containment
Composition, μg		
Fuel (as oxide)	1.53×10^{11}	1.53×10^{11}
Volatile solids	4.50×10^{10}	4.50×10^{10}
Halogens	2.80×10^{9}	2.80×10^{9}
Na_2O	6.38×10^{11}	2.99×10^{10}
Total	8.39×10^{11}	2.31×10^{11}
Gas volume, cm^3	6.4×10^{10}	8.2×10^{8}
Initial aerosol mass concentration, $\mu g/cm^3$	13.1	280
Initial concentration, particles/cm^3	7.95×10^{7}	7.70×10^{8}
Particle Density, g/cm^3	2.74	6.0
Particle density modification factor, α	0.25	0.25
Initial particle mass median diameter (MMD), μm	1.0	1.0
Geometric standard deviation, σg	2.0	2.0
Mass fraction as Pu	0.0402	0.146

TABLE 3

COMPARISON OF CONTAINMENT CONCEPTS

(for Source Term and Reference Plant Designs Defined in this Paper)

	Single Containment			Double Containment		Containment/ Confinement	
	No Cleanup	Natural Fallout, $\alpha=0.25$	With EACS, $\lambda=5\ hr^{-1}$	Natural Fallout, $\alpha=0.25$	With EACS, $\lambda=2\ hr^{-1}$	EACS CF=100	EACS DF=1000
TOTAL MASS LEAKED, g							
2 hours	110	43.	11.	0.05	0.014	3.5	0.35
t = 30 days	4.3×10^4	48.	11.	0.5	0.015	5.6	0.56
PLUTONIUM LEAKED, g							
2 hours	2.8	1.2	0.27	0.0073	0.002	0.51	0.051
t = 30 days	1100	1.4	0.27	0.073	0.0022	0.81	0.081
BONE DOSE @ 1 MILE, rem							
2-hour exposure	650	270.	62.	1.8	0.5	6.3	0.63
30-day exposure	2.4×10^5	320.	62.	18.	0.54	10.	1.
BONE DOSE @ 6.2 MILE, rem							
30-day exposure	1.8×10^4	23.	4.5	1.3	0.04	4.5	0.45

environment. Using standard meteorological data,(9) an arbitrary site exclusion radius of 1 mile (1609 m) and a population center distance of 6.2 miles (10,000 m), the bone doses are calculated for the three reference containment designs. The information is presented for plants with and without an EACS operating, and for two EACS efficiency levels for the containment/confinement plant. The ranking, in order of ascending dose, is the same at each distance and is as follows:

Rank	System
1	Double Containment with EACS
2	Containment/Confinement, DF=1000
3	Double Containment without EACS
4	Containment/Confinement, DF=100
5	Single Containment with EACS
6	Single Containment without EACS

The comparison of containment systems made in Table 3 indicates that, if a double containment system is provided, an EACS may not be required. This conclusion cannot be substantiated until additional information becomes available on accidents not considered in this report, e.g., a reactor melt-through, and until federal regulations are established for accident guideline dose limits on plutonium inhalation. However, for the accident conditions described here and for the presently suggested guideline bone dose of 150 rem, it appears that for a double containment plan an EACS would not be required to meet most siting requirements, although it would certainly add to the margin of safety. Therefore, for the purpose of evaluating EACSs for development, only the single containment and containment/confinement type systems will be considered at this time. Table 4 presents the most probable ranges of values for the important accident conditions which impact EACS design for the remaining two containment systems. Because a sodium fire in the confinement building would impose a severe loading on the EACS, Table 4 also includes a list of environmental conditions for the case of a postulated large sodium fire in the confinement building. For the purposes of this report, it is assumed that the DBST and the sodium fire would not occur simultaneously.

IV. Criteria and Procedure for Evaluating EACS Concepts

The conservative EACS operating conditions have been summarized in Table 4 for the two containment systems. Because of the obvious differences in EACS requirements for these two systems, separate evaluation criteria have been defined for both types of containment. For each case, the criteria are classed into six main groups, each with several individual criteria. Table 5 lists the criteria for single containment.

Somewhat different criteria have been developed for the containment/confinement system. For this containment concept, the EACS is an integral part of the plant confinement design and, as a result, a minimum decontamination factor of 100 is specified and the weighting factors have been changed somewhat, with additional weight being placed on the reliability and compatibility sections. The criteria for evaluating an EACS in containment/confinement systems are given in Table 6. The total of the weighting factors remains at 100, as in

TABLE 4

PARAMETERS CHARACTERIZING ACCIDENT ENVIRONMENT FOR TWO CONTAINMENTS WITH EACS

Parameter	Probable Value for Single Containment[(a)]	Probable Values[(c)] for Confinement Bldg.	
		DBST[(d)]	Sodium Fire
1. Aerosol source	Puff release followed by sodium pool fire. Upper bound 1% of fuel, 25% halogens, 25% volatile solids, 100% noble gases, 5000 lbs sodium	Leakage from primary containment after HCDA	40 lb/min sodium released into confinement bldg
2. Maximum containment gas temperature	300°F	-10 to 110°F	-10 to 300°F
3. Maximum containment pressure	10 psig	0 psig	0 psig
4. Containment pressure transient	0.2 psi/sec for 15 sec	0	0
5. Containment atmosphere humidity	0 to saturated	10 - 100% RH	0 - 100% RH
6. Maximum aerosol mass concentration	20 $\mu g/cm^3$	0.02 $\mu g/cm^3$	25 $\mu g/cm^3$
7. Mass collected by EACS (maximum)	2000 kg	1 kg	1000 kg[(e)]
8. Water/sodium weight ratio for aerosol particle	0 - 10	1 - 100	1 - 10
9. Aerosol size distribution	1.7 μm MMD, $\sigma = 2$	4.0 μm MMD, $\sigma = 2$	2 μm MMD, $\sigma = 2$
10. Particle material density	2.7 g/cm^3	6 g/cm^3	2.3 g/cm^3
11. Particle density modification factor	0.25	0.25	0.25
12. Effective density of particles	0.7	0.25	0.25
13. Aerodynamic equivalent diameter[(b)]	1.4 μm AED	1.5 g/cm^3	0.6 g/cm^3
14. FP decay heat in EACS collected mass 10^6 Btu/hr			
t = 1 hr	10	.01	0
t = 2 hr	10	.01	
t = 7 hr	5	.01	
t = 24 hr	3	.007	

(a) EACS $\lambda = 5\ hr^{-1}$

(b) equivalent particle with density of 1.0 g/cm^3

(c) for 15,000 CFM ventilation rate

(d) not considering a sodium fire in confinement building

(e) as NaOH

TABLE 5

CRITERIA FOR EVALUATING LMFBR EMERGENCY AIR CLEANING SYSTEMS IN SINGLE CONTAINMENT PLANTS

Criteria Description	Weight Factor	
1. SYSTEM EFFECTIVENESS		27
The EACS shall be effective in reducing the release of radioactive substances to the environment under DBST conditions.		
a. A dose reduction factor (2-hr) of ten can be achieved for aerosol particles	9*	
b. Decay heat can be dissipated adequately	7*	
c. Either dry or sticky particles can be treated effectively	7*	
d. System effectiveness is not degraded by the radiation dose caused by the accident over the required operating period	4*	
2. SYSTEM RELIABILITY		23
The EACS shall have a high degree of reliability in startup and continuance of operation during the entire accident period.		
a. The EACS shall have a high probability of startup after initiation of the DBST release	6*	
b. The system shall be capable of withstanding the pressure pulse associated with the DBST	5*	
c. The system does not degrade during periods of unuse	4*	
d. The system shall be capable of dependable operation over the required period of time under accident conditions of temperature, pressure, humidity and aerosol loading	6*	
e. The system requires simple components and conservative design stress	2	
3. CONTAINMENT COMPATIBILITY		18
The presence and operation of the EACS shall not degrade the normal effectiveness of the containment building.		
a. Inadvertent operation of the EACS shall not harm plant equipment or constitute a hazard to personnel	5	
b. Operation of the EACS shall not significantly increase the pressure within the containment building by gas injection, energy release or other means	5*	

* denotes mandatory criterion.

TABLE 5 (continued)

	Criteria Description	Weight Factor	
c.	The size of the EACS shall be compatible with installation within or adjacent to the containment building (less than 10% of the volume of the RCB)	4*	
d.	The EACS shall maintain the collected aerosol mass in a subcritical configuration	4*	
4.	TECHNOLOGICAL CREDIBILITY		14
	The effectiveness of the EACS shall be clearly demonstrable by experience, mathematical models and testing.		
a.	The air cleaning concept is based on highly developed technology	3	
b.	The EACS can be tested in-place for operability and efficiency	5	
c.	The EACS performance can be predicted by verified mathematical models	4	
d.	The EACS equipment scaleup from currently available sizes to LMFBR plant application is small	2	
5.	SYSTEM CHARACTERISTICS AND FLEXIBILITY		11
	The EACS performance shall not be critically dependent on the accident environment conditions and shall accommodate possible future design changes.		
a.	The EACS is effective for the entire particle size spectrum expected during the accident	3	
b.	The system performance is not highly sensitive to the atmosphere temperature, pressure and relative humidity	4	
c.	The system energy consumption is low	1	
d.	The system can be modified to add halogen removal components, hydrogen recombiners, containment coolers	2	
e.	The post-accident recovery is facilitated by the EACS	1	
6.	FABRICATION EFFORT		7
	The system shall be readily designed, fabricated and installed at reasonable cost and in a time frame consistent with plant construction.		
a.	The system cost is low. Capital cost is less than $10 million; operating costs are low	5	
b.	Materials and techniques used in construction are readily available and easily fabricated	1	
c.	Components and equipment are readily available	1	
			100

TABLE 6

CRITERIA FOR EVALUATING LMFBR EMERGENCY AIR CLEANING IN A CONTAINMENT/CONFINEMENT PLANT

Criteria Description	Weight Factor	
1. SYSTEM EFFECTIVENESS		24
The EACS shall be effective in reducing the release of radioactive substances to the environment under DBST conditions.		
a. A decontamination factor of 100 can be achieved for aerosol particles	12*	
b. Either dry or sticky particles can be treated effectively	7*	
c. System effectiveness is not degraded by the radiation dose caused by the accident over the required operating period	5*	
2. SYSTEM RELIABILITY		29
The EACS shall have a high degree of reliability in startup and continuance of operation during the entire accident period.		
a. The EACS shall have a high probability of startup after initiation of the DBST release	10*	
b. The system does not degrade during periods of unuse	6*	
c. The system shall be capable of dependable operation over the required period of time (30 days for DBST, 1 day for Na fire) under the accident conditions of temperature, pressure, humidity, and aerosol loading	10*	
d. The system requires simple components and conservative design stresses	3	
3. CONTAINMENT COMPATIBILITY		7
The presence and operation of the EACS shall not degrade the normal effectiveness of the confinement building.		
a. Inadvertent operation of the EACS shall not harm plant equipment or constitute a hazard to personnel	4	
b. The size of the EACS shall be compatible with installation within or adjacent to the confinement building (<12,000 ft^2)	3*	
4. TECHNOLOGICAL CREDIBILITY		21
The effectiveness of the EACS shall be clearly demonstrable by experience, mathematical models and testing.		
a. The air cleaning concept is based on highly developed technology	5	

* denotes mandatory criterion.

TABLE 6 (continued)

	Criteria Description	Weight Factor	
b.	The EACS can be tested in-place for operability and efficiency	8*	
c.	The EACS performance can be predicted by verified mathematical models	5	
d.	The EACS equipment scaleup from currently available sizes to LMFBR plant application is small	3	
5.	SYSTEM CHARACTERISTICS AND FLEXIBILITY		12
	The EACS performance shall not be critically dependent on the accident environment conditions and shall accommodate possible future design changes.		
a.	The EACS is effective for the entire particle size spectrum expected during the accident	3	
b.	The system performance is not highly sensitive to the atmosphere temperature, pressure and relative humidity	4	
c.	The system energy consumption is low	2	
d.	The system can be modified to add halogen removal components and other air cleaning devices if needed	2	
e.	The post-accident recovery is facilitated by the EACS	1	
6.	FABRICATION EFFORT		7
	The system shall be readily designed, fabricated and installed at reasonable cost and in a time frame consistent with plant construction.		
a.	The system cost is low. Capital cost is less than $10 million; operating costs are low	5	
b.	Materials and techniques used in construction are readily available and easily fabricated	1	
c.	Components and equipment are readily available	1	
			100

the previous case.

Certain criteria are thought to be of such importance to the system that they are considered mandatory requirements and a minimum rating score of 2.0 is required. These mandatory criteria are noted in Tables 5 and 6 by an asterisk.

Using the requirements established previously in Table 4 for the EACS design base, a conceptual design of the candidate air cleaning system was completed. On the basis of this preliminary design, the system was rated with a score of 0 to 4 (to the nearest 0.1), based on the extent that it met each criterion.

A system score is determined by summing the individual criterion scores which are the product of the criterion weight and the rating factor. The maximum system score possible is 400. Systems with criteria with low scores were examined for possible design changes which could lead to improved ratings.

Scope Design of Systems

As noted above, ratings were obtained for systems based on the preliminary design. These systems were examined for possible areas of improvement and several promising systems were designed in more detail. Whenever possible, performance information for removal of alkali metal fumes was used.(10-13) For many systems, however, such information was not available and the designs were based on conservative interpretation of standard air cleaning texts and reports.

V. Description of Air Cleaning Systems Evaluated

System Classification

The chief radiological hazards resulting from the DBST defined in Section III are the plutonium and solid fission products released to the containment building as respirable-size aerosol particles. Radioactive materials released in other forms, e.g., halogen vapor and noble gases, are of concern and their hazard should be investigated. However it is believed that most of the halogens would be associated with aerosol particles(14,15) and that the chief air cleaning objective is the removal of the aerosol particles. Consequently, the systems selected for evaluation in this report are aimed at removal of particulates. Iodine removal may become the objective of future studies.

Many types of air cleaning equipment are available for controlling particulate air pollutants. They can be classified into three general groups according to their mode of operation in LMFBR service: (1) gas recirculation, (2) direct in-vessel application, and (3) gas purge. In the gas recirculation mode, the EACS removes the contaminants from a flowing gas stream in a recirculating loop which can be located either entirely internal or external to the containment building. Direct in-vessel application systems operate directly on the containment building atmosphere without incorporating a duct air flow system. An example of this class is the containment building spray system used in many LWR plants. In the gas purge mode (also known as single-pass mode), the EACS is located in a ventilation system which discharges directly to the environs usually through a stack.

Air Cleaning Systems to be Evaluated

Particle removal from the containment atmosphere may be accomplished by air cleaning components used singly or several types may be arranged into systems. The types of components and systems considered in this study are listed in Table 7.

TABLE 7
TYPES OF CANDIDATE AIR CLEANING COMPONENTS AND SYSTEMS

For Recirculating or Purge Modes

- Filters
  - Prefilters (various types, including demisters)
  - Bag Filters (various types)
  - Deep Bed Graded Media Filters
  - Sand Filters
  - High-Efficiency Particulate Air (HEPA) Filters
- Cyclone Separators
- Mechanical Separators
- Electrostatic Precipitators
  - Dry
  - Wet
- Wet Scrubbers
  - Spray Chamber
  - Centrifugal Scrubber
  - Venturi Scrubber
  - Packed Bed
- Fluidized Bed
- Acoustic Agglomerator
- Settling Chamber
- Charcoal Bed

For Direct In-Vessel Application Modes

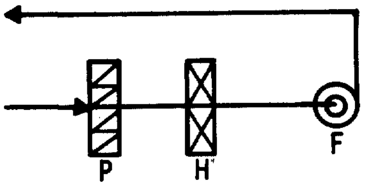
- Containment Building Liquid Spray
- Containment Building Powder Discharge
- Foam Dispersal
- Acoustic Agglomerator
- Electrostatic Precipitator

These components are arranged into the systems shown in Figure 1 for study in the single containment case. Figure 2 shows the systems for the containment/confinement case.

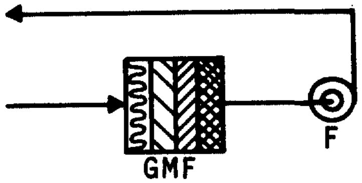
VI. Evaluation Results

Numerical Ratings for EACSs

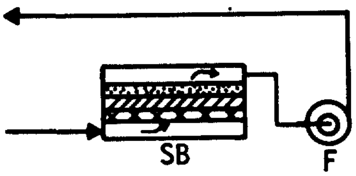
The numerical ratings and weighted group scores for both single containment and containment/confinement plant systems are tabulated in Table 8. The ratings represent the best judgment of the authors and were arrived at after both independent and joint assessments of how well each criterion was satisfied on a system-by-system basis. Quantitative evaluations were possible for some of the criteria (e.g., cost, size, DRF, energy requirement), but many of the criteria ratings were assigned on a subjective basis.



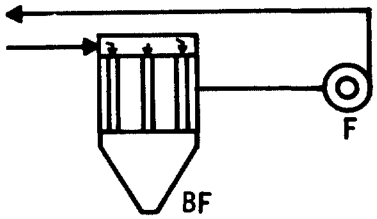
SR-1 RECIRCULATING-
PREFILTER, HEPA



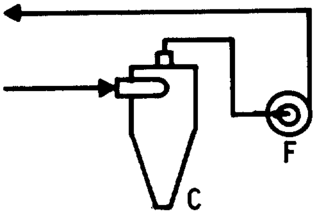
SR-2 RECIRCULATING-
GRADED MEDIA FILTER



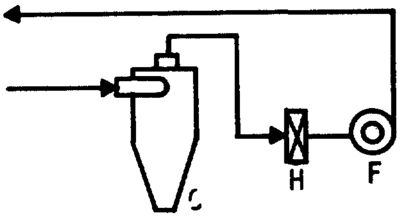
SR-3 RECIRCULATING-
SAND BED FILTER



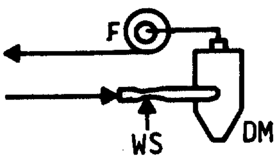
SR-4 RECIRCULATING-
BAG FILTER



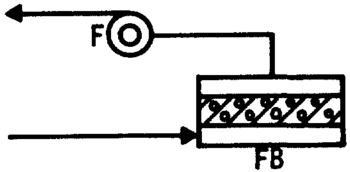
SR-5 RECIRCULATING-
CYCLONE SEPARATOR



SR-6 RECIRCULATING-
CYCLONE, HEPA

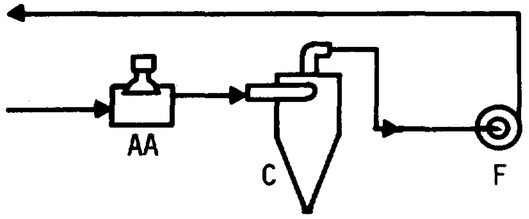


SR-7 RECIRCULATING-
WET SCRUBBER,
DEMISTER

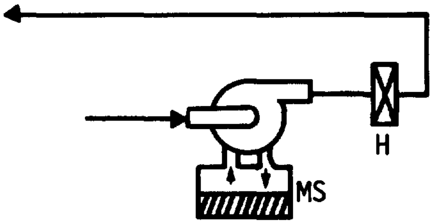


SR-8 RECIRCULATING-
FLUIDIZED BED

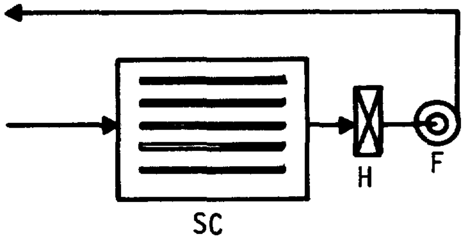
FIGURE 1a. Schematic Flow Diagrams for Single Containment EACS Candidate Systems.



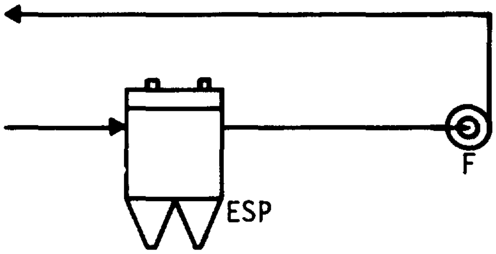
SR-9 RECIRCULATING - ACOUSTIC AGGLOMERATOR, CYCLONE



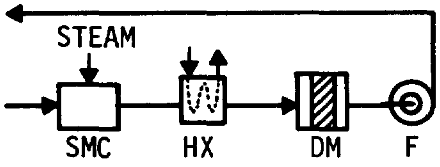
SR-10 RECIRCULATING - MECHANICAL SEPARATOR, FILTER



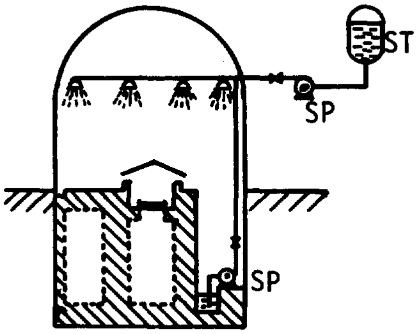
SR-11 RECIRCULATING - SETTLING CHAMBER, FILTER



SR-12 RECIRCULATING - ELECTROSTATIC PRECIPITATOR

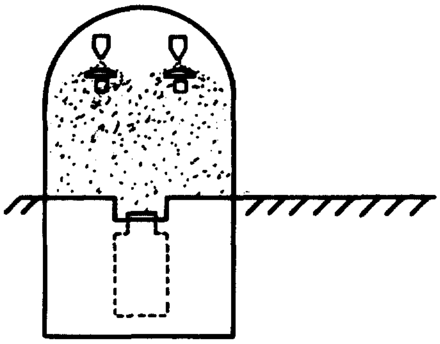


SR-13 RECIRCULATING - STEAM CONDITIONER, DEMISTER

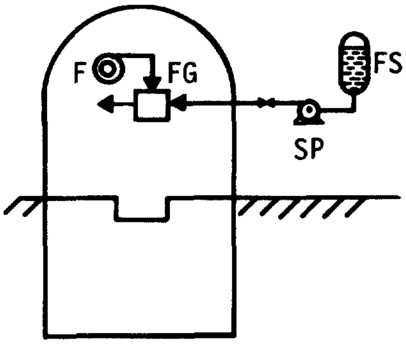


SD-14 DIRECT LIQUID SPRAY

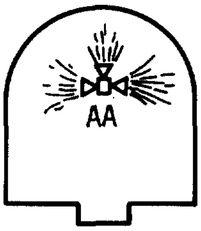
FIGURE 1b. Schematic Flow Diagrams for Single Containment EACS Candidate Systems.



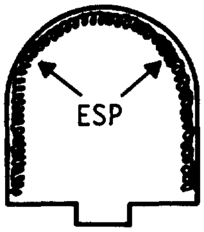
SD-15 DIRECT POWDER DISCHARGE



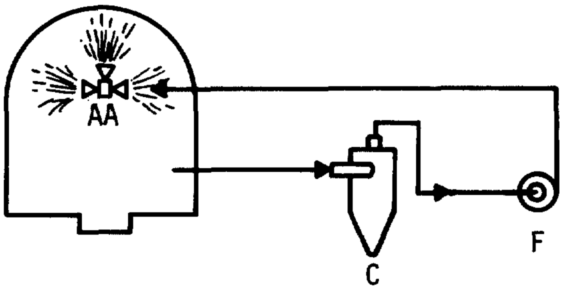
SD-16 DIRECT FOAM DISPERSAL



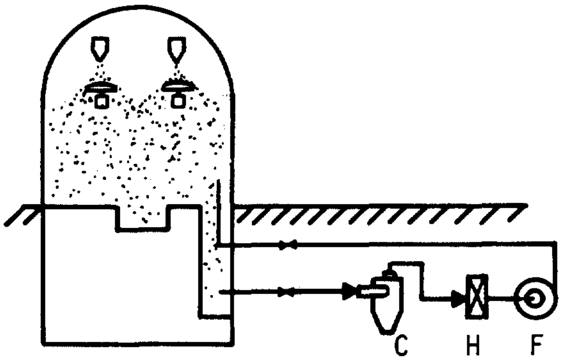
SD-17 DIRECT ACOUSTIC AGGLOMERATOR



SD-18 ELECTROSTATIC PRECIPITATOR

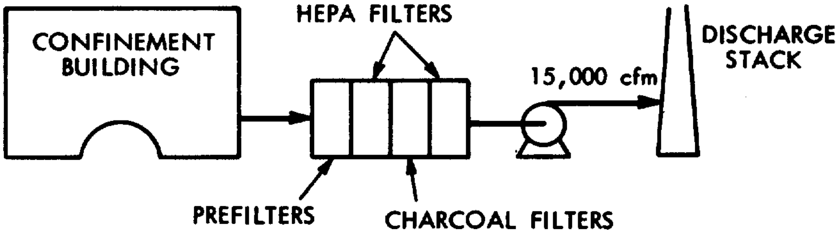


SC-19 COMBINATION - ACOUSTIC AGGLOMERATOR PLUS RECIRCULATING CYCLONE

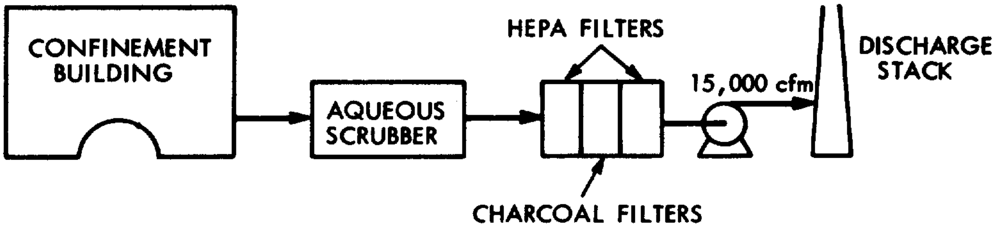


SC-20 COMBINATION - POWDER DISCHARGE PLUS RECIRCULATING CYCLONE, FILTER

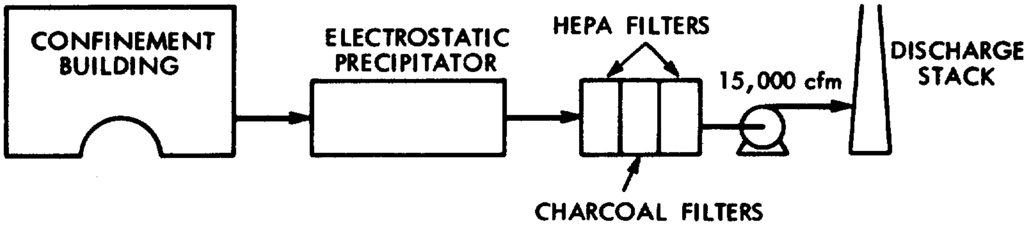
FIGURE 1c. Schematic Flow Diagrams for Single Containment EACS Candidate Systems.



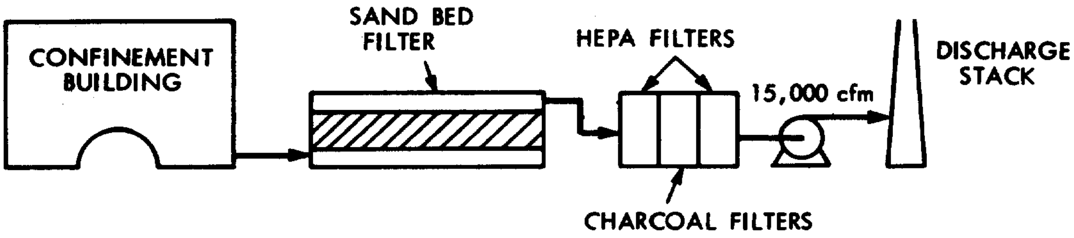
SYSTEM CF-21. PREFILTER, HEPA, CHARCOAL, HEPA



SYSTEM CF-22. SCRUBBER, HEPA, CHARCOAL, HEPA



SYSTEM CF-23. ELECTROSTATIC PRECIPITATOR, HEPA, CHARCOAL, HEPA



SYSTEM CF-24. SAND FILTER, HEPA, CHARCOAL, HEPA

FIGURE 2. Schematic Diagrams for Containment/Confinement Air Cleaning Systems Evaluated.

TABLE 8

RANKING OF EACS CANDIDATES BY TOTAL SCORE AND BY CRITERIA GROUPS

				Ranking by Criteria Group[a]					
Overall Rank	System		Total Score	Group 1 Effectiveness	Group 2 Reliability	Group 3 Compatibility	Group 4 Credibility	Group 5 Flexibility	Group 6 Fabrication
Single Containment Systems									
1	SR-1	PF + HEPA	338.8	16	5	2	1	5	11
2(b)	SR-3	Sand bed	338.4	8	1	10(b)	2	4	18
3	SR-6	Cyclone + HEPA	327.5	11	4	8	7	9	8
4	SR-12	Electrostatic	325.7	13	12	4	4	2	13
5	SR-5	Cyclone	324.2	10	2	9	8	19	5
6	SR-2	Graded media	322.1	14	3	6	10	6	16
7	SR-4	Bag filter	313.1	18	14	5	3	7	7
8(b)	SR-7	Wet scrubber	310.7	7	11	17(b)	6	10	12
9	SD-17	In-containment acoustic	309.5	1	7	15	16	16	4
10	SR-9	Recirc acoustic + cyclone	306.5	9	9	12	14	8	15
11	SC-19	In-cont acoustic + recirc cyc	304.6	3	8	16	15	11	9
12(b)	SR-11	Settl Bed + HEPA	304.5	15	16	13(b)	5	12	20
13(b)	SD-14	Liquid spray	296.8	4	10	19(b)	11	13	1
14	SD-15	In-containment powder	296.4	2	16	11	18	14	6
15(b)	SR-10	Mech Sep + HEPA	293.0	19(b)	13(b)	3	9	17	10
16	SC-20	Powder + recirc HEPA	288.7	5	18	14	17	3	14
17(b)	SR-13	Steam + demister	276.7	6	19	18(b)	13	1	17
18(b)	SR-8	Fluidized bed	272.6	12	20(b)	1	12	15	19
19(b)	SD-18	Direct ESP	254.9	20(b)	15	7	20	18	2
20(b)	SD-16	Foam	237.9	17(b)	17(b)	20(b)	19	20	3
Containment/Confinement Systems									
1	CF-24	Sand bed	356.0	2	1	4	1	1	4
2	CF-21A	PF, HEPA	341.0	4	2	2	2	2	2
3	CF-23	ESP	336.0	3	3	1	3	3	1
4	CF-22	Wet scrubber	328.0	1	4	3	4	4	3

(a) See Tables 5 and 6 for complete definition of criteria

(b) Denotes failure of one or more mandatory criteria

As noted in Table 8, nine of the single containment systems rated unacceptably low in the mandatory criteria identified in Table 5. Two of the systems failed because of their large size (SR-3, sand bed; and SR-11, settling bed plus HEPA). Although the size criterion is somewhat arbitrary, it is felt that the added containment volumes required for the sand bed (22 percent of the RCB volume) and the settling bed (45 percent) are clearly excessive. Four systems failed because they used water which creates a potential hydrogen problem (SR-7, wet scrubber; SR-13, steam conditioner; SD-14, liquid spray; and SD-16, foam). If a suitable alternate liquid could be found to replace water in these systems, they would rate much higher and the SD-14 liquid spray system would probably be the best overall system. Two systems failed because of unacceptably low reliability for operating throughout the required period of time (SR-8, fluidized bed; and SR-10, mechanical separator plus HEPA filters). Both of these are sensitive to handling sticky particles. One system failed because it was ineffective in providing a reasonable dose reduction factor (SD-18, in-containment electrostatic precipitator).

Of the eleven single containment EACSs remaining after elimination of the failed systems, the system with the highest overall rating is the recirculating-prefilter/HEPA system, SR-1. System CF-24, the sand bed filter, had the best rating for the containment/confinement plant.

The scores of the surviving containment plant systems were reviewed to determine the development potential.

Discussion of Ratings

Table 8 shows that the recirculating systems rank higher in total score than those which act directly in containment. Closer examination of Table 8 reveals that this is due to the generally low ratings given the in-containment concepts for reliability, compatibility, credibility, and flexibility. The in-containment concepts (acoustic agglomeration and powder dispersal, either singly or in combination with recirculating systems) rate very high in effectiveness and fabrication. This suggests that if development effort can improve the credibility, reliability and compatibility of the two in-containment concepts they would probably become the best EACS candidates. It seems probable that the credibility group ratings, at least, could be improved considerably by proper development effort.

Figure 3 illustrates that the two in-containment concepts (SD-15, powder dispersal; and SD-17, acoustic agglomeration) or combination systems using these two concepts (SR-9, SC-19, SC-20) are generally low in credibility but high in effectiveness. The diagonal line in Figure 3 arbitrarily separates the systems into those which offer high and low incentive for improvement by development effort. The systems furthermost to the left of the line offer the most potential. Similarly, Figure 4 plots the reliability versus the credibility ratings.

Another criterion which can be used to select the most promising EACS for development is cost. In Figure 5, the numerical ratings are plotted versus the estimated installed cost for all twenty systems evaluated. The nine systems which failed the mandatory criteria are

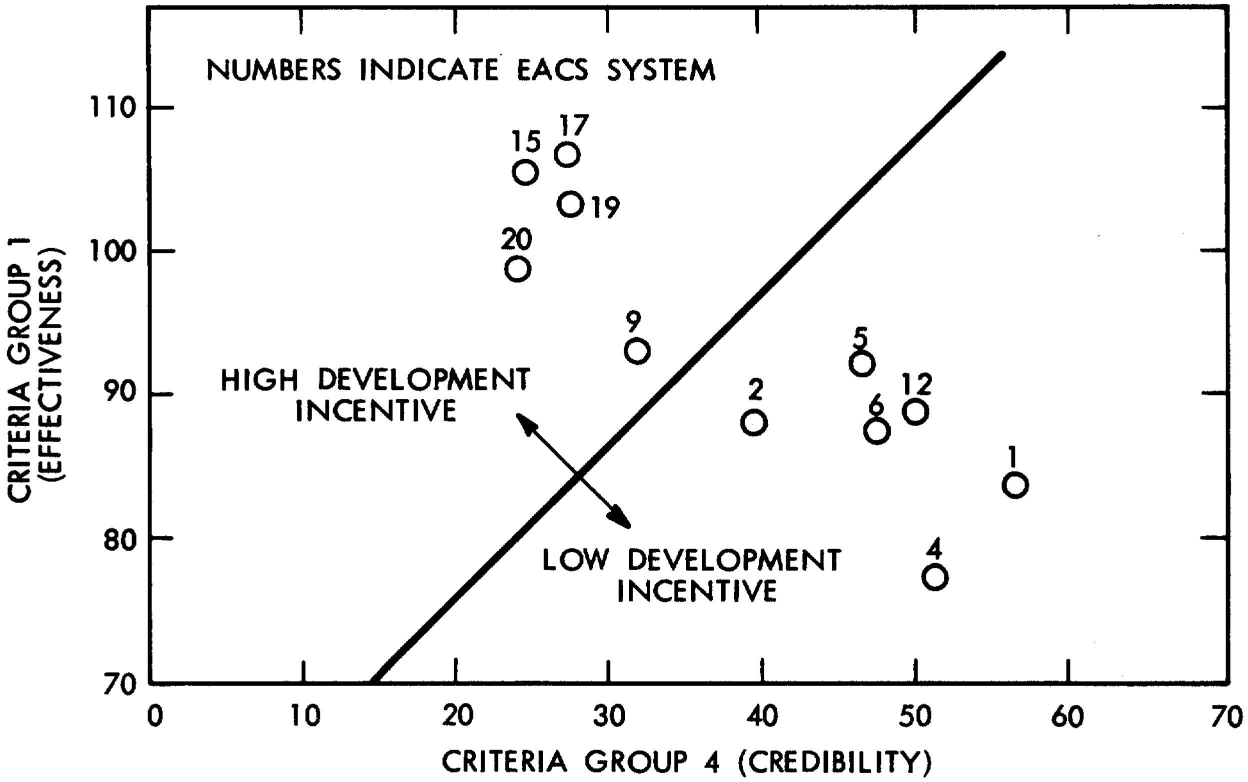


FIGURE 3. EACS Effectiveness Versus Credibility Ratings.

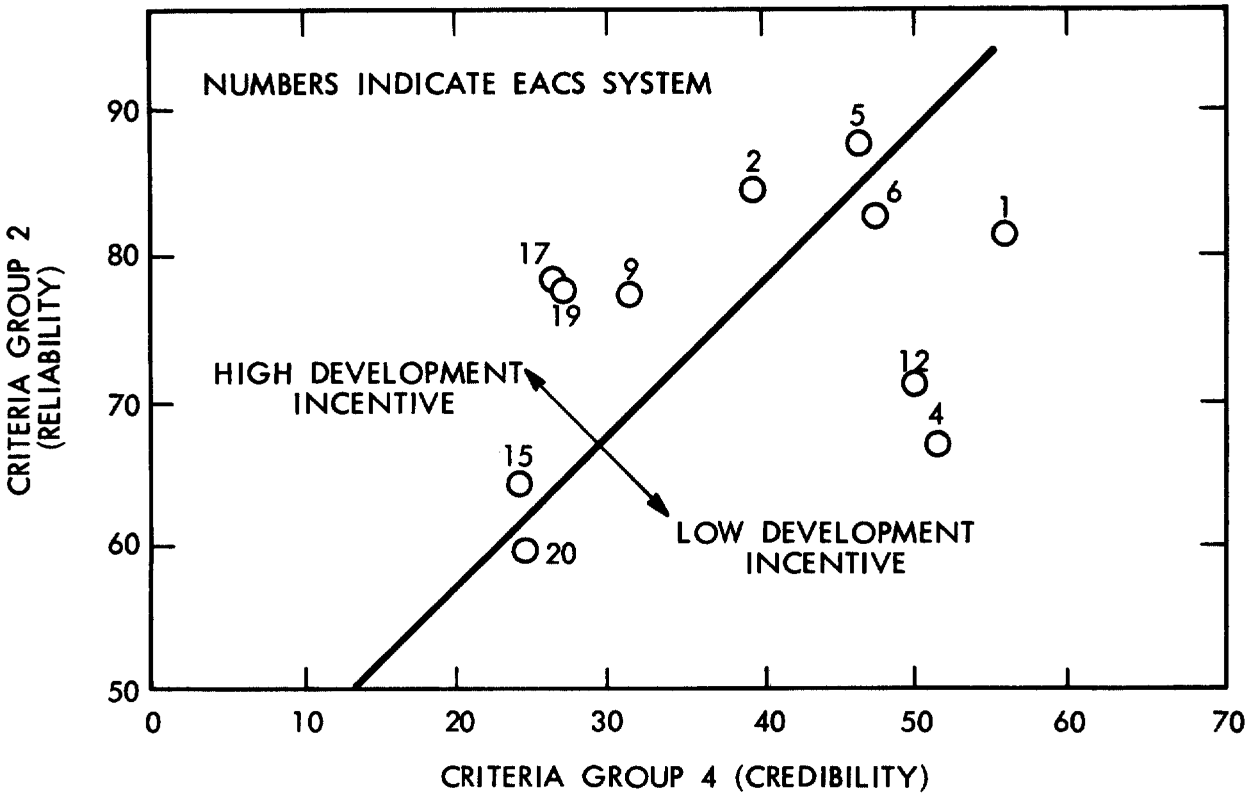


FIGURE 4. EACS Reliability Versus Credibility Ratings.

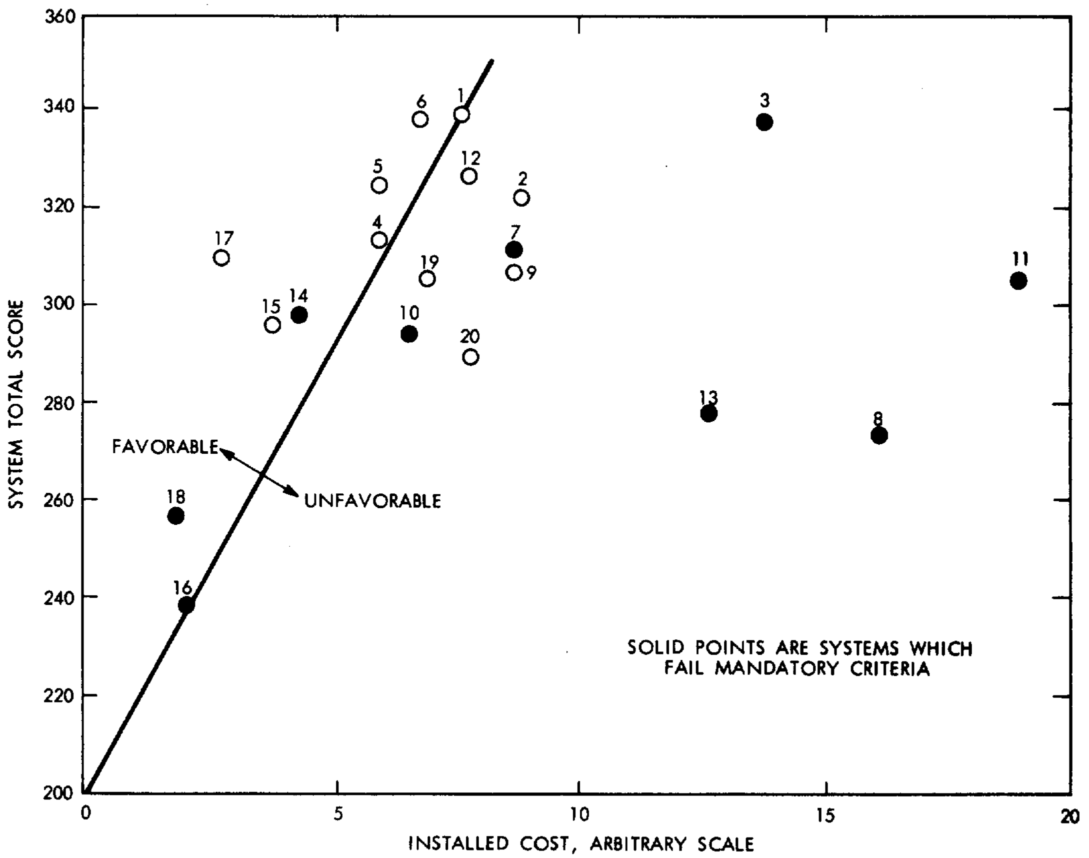


FIGURE 5. EACS Numerical Ratings Versus System Cost.

designated by solid symbols, while the remaining eleven systems are plotted with open symbols. Since low cost and high numerical ratings are desirable, systems lying to the left of the diagonal line are the more favorable candidates. On a cost basis, system SD-17 (in-containment acoustic agglomeration) is the best system, having a reasonably high rating with the lowest cost of any of the eleven feasible systems. The powder dispersal system (SD-15) and the two cyclone systems (SR-5 and SR-6) are also cost-favorable.

Table 9 summarizes the system components which are regarded as being favorable for development, based on their use in systems which show the highest development potential. The specific development recommendations for these concepts are given in Table 10.

The analysis of the numerical ratings for containment/confinement EACS concepts is more direct, as no systems failed the mandatory criteria and fewer systems were involved. Table 8 shows that system CF-24 (sand bed - HEPA - charcoal - HEPA) has the highest total score. Second highest is system CF-21A (prefilter - HEPA - charcoal - HEPA); third is CF-23 (electrostatic precipitator - HEPA - charcoal - HEPA); and fourth is CF-22 (wet scrubber - HEPA - charcoal - HEPA).

It is not reasonable to compare system CF-21B (conventional prefilter - HEPA - charcoal - HEPA) with the other four systems because it is not designed to handle the sodium fire accident. However, it was

TABLE 9

AIR CLEANING CONCEPTS FAVORED FOR DEVELOPMENT FOR LMFBR SINGLE CONTAINMENT PLANTS

Air Cleaning Concept or Device	Number of Times Favored*
High-Efficiency Cyclone Separator	9
Acoustic Agglomeration	7
Powder Dispersal	4
HEPA Filters	3
Deep Bed Graded Media Filter	2
Prefilter	1
Electrostatic Precipitator	1
Bag Filter	1

*From Figures 3, 4, and 5

rated on an absolute basis against the DBST conditions and was assigned a total score of 382. Although it was not given a perfect score of 400, this system clearly met or exceeded every criterion for the DBST case.

It is concluded that on the basis of present knowledge the sand bed filter system, CF-24 (backed up by a HEPA -charcoal -HEPA), is the best system for cleaning the confinement building exhaust if the EACS must handle both the DBST and a sodium fire in the confinement building. A conventional prefilter-HEPA-charcoal-HEPA system (CF-21B) is best if a sodium fire is excluded. If two parallel, independent systems can be shown to be feasible, then the best combination is the CF-21B filter-adsorber system for handling the radiologically significant DBST and a separate system using only a wet scrubber (without backup filters) for handling the sodium fire accident effluent.

Development needs for the containment/confinement systems are also presented in Table 10. The development activities described here represent a compilation of the necessary data and confirmatory information found lacking during the conceptual design and evaluation of the EACS. Completion of the development would lead to improved design and increased confidence in the air cleaning systems.

VII. Conclusions

The work reported here substantiates the conclusion that reliable and effective EACSs are feasible for use as engineered safety systems for LMFBR plants, but that some development effort is needed for all the air cleaning concepts evaluated. The work supports the following specific conclusions:

1. Air cleaning is a promising engineered safety system for LMFBRs. It is virtually certain that a 2-hr DRF of 10 can be achieved with systems designed for single containment and that decontamination factors of 100 to 1000 can be obtained by systems designed for containment/confinement plants.

TABLE 10
DEVELOPMENT NEEDS FOR RECOMMENDED EACS CONCEPTS

Single Containment

Priority	Concept or Device	Development Needed
1.	Prefilter and HEPA	a) Loading capacity as a function of aerosol composition, particle size, air humidity. b) Long-term performance--chemical attack, change in flow resistance, resuspension. c) Large-scale demonstration under simulated DBA conditions.
2.	Acoustic Agglomeration	a) Measurement of agglomerated particle size and density as a function of sound intensity, frequency, wave shape; and particle concentration, size, density. Small-scale and large-scale tests. b) Theoretical treatment of acoustic agglomeration process relating particle size to acoustic conditions. c) Develop high-intensity sound generator, minimizing gas requirement.
3.	Cyclone Separator (High-Efficiency Type)	a) Large-scale demonstration tests in simulated DBA conditions: 1) Alone 2) Pretreatment for filter 3) Backup for in-line acoustic agglomerator.
4.	Powder Discharge	a) Develop suitable powder (storage, flowability, dispersibility, reaction with Na fire). b) Demonstrate aerosol removal in a large vessel, verifying mathematical model predictions of effects of powder size, flow rate and fall height. c) Demonstrate full-scale equipment for storing and dispersing powder.

Containment/Confinement

Priority	Concept or Device	Development Needed
1.	Sand Bed	a) Optimize sand and gravel layers to give maximum Na_2O/NaOH loading capacity. b) Characterize sand bed (1.a. above) performance. Efficiency, flow-resistance as function of aerosol particle size, concentration and gas relative humidity. c) Proof test large-scale section of prototype sand bed under simulated DBA conditions.
2.	HEPA	Same as No. 1 for single containment.
3.	Wet Scrubber	Measure efficiency for Na_2O/NaOH particle removal as function of particle size, using three types of scrubbers (wetted fiber bed, Venturi, centrifugal wet fan) at large scale (5 to 10,000 CFM).

2. The technological base for air cleaning of LMFBR plants is not sufficient to support an immediate application. For the most developed system currently available, development efforts appear to be modest. Lesser developed but potentially more attractive systems are available, and development applied to these would have a potentially high payoff in terms of reduced system cost and possibly higher DRFs.

3. For single containment plants, the best system, judged from current technology, is a recirculating system with low efficiency prefilters followed by high-efficiency particulate air (HEPA) filters. Direct in-containment acoustic agglomeration of aerosols is a highly attractive candidate system because it is small in size and low in cost. Considerably more development effort would be required to allow firm design of the acoustic agglomerator system than for the recirculating prefilter-HEPA system. A third system which appears promising is direct in-containment powder discharge, which is small and intermediate in cost. Cyclone separators were found to have usefulness individually and in combination with other components because of their high mass loading capacity and simplicity. Several other systems were judged to be feasible but less desirable because of higher cost, size, or lower reliability.

4. All systems which use liquids were judged to be unfeasible for use in single containment plants because no suitable liquid could be identified. The vapor pressure and hydrogen formation potential of aqueous liquids prevented their use. Several of these systems would be very attractive if a suitable liquid could be identified.

5. For a containment/confinement plant with a design basis source term encompassing both a radiological release and a sodium fire, the best system, judged from current technology, is a sand and gravel bed filter backed up by a HEPA-charcoal adsorber system. A significant reduction in the relatively high cost is believed possible by development of a sand bed with a high mass loading capacity. If the containment/confinement plant source term excludes a sodium fire, the best system is a conventional filter-adsorber system consisting of prefilters, HEPA filters, and charcoal adsorbers.

6. If two parallel, independent systems can be shown to be feasible, then the best combination for a containment/confinement plant is the filter-adsorber system for handling the radiologically significant source term and a separate wet scrubber system (without back-up filters) for handling the sodium fire accident effluents.

7. An aerosol property which is poorly understood but which can have an impact on the performance of some types of EACSs is the stickiness and change of particle shape caused by adsorption of water vapor. Normal reactor containment building (RCB) atmospheres contain sufficient moisture and carbon

dioxide to convert all of the released sodium oxide aerosol to sodium hydroxide and sodium carbonate. Additional water release from concrete surfaces exposed to the RCB atmosphere must be considered.

8. The 2-hr DRF provided by all the systems evaluated here was 10 because this was a design objective. Larger or smaller systems can be designed, yielding proportionate values of cost and DRF.

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DISCUSSION

MOELLER: How did you determine the reliability of each of the various systems you considered?

MCCORMACK: We did not go into any detailed failure analysis. It was, in this case, fairly subjective with the authors and it was a relative ranking rather than any absolute system.

KAHN: In the first ranking of the containment systems, you had an asterisk next to the sand filter, indicating failure to meet a mandatory criterion. Was cost the mandatory criterion involved?

MCCORMACK: No, cost really isn't a mandatory criterion, but size is, and it was primarily size that gave us trouble with the sand filter. We felt that the filter housing would have to be built with the same code requirements as the containment vessel. With a system the size of a sand filter, we felt that this was a very serious obstacle.

SCHIKARSKI: Have you looked into the German sand filter design, which is a very small, compact kind?

MCCORMACK: Yes. We used some of your loading information in attempting our scope design. It is interesting that we think this is an application where, perhaps, the sand filter could be optimized to reduce size even further and to increase mass loading even if the cost was a somewhat reduced efficiency.

SCHIKARSKI: In my opinion, your ranking for the cyclones is too high to be realistic. There is much evidence that many designs of cyclones can be plugged easily by sodium oxide aerosols during long-term operation. Did you take this into account?

MCCORMACK: We were very concerned about the sticking of the sodium oxide or sodium hydroxide particles. This was a concern with us in the scope design of the systems. We didn't have any definite information on that feature.

BENDIXSEN: I noticed in both of your figures that the relative rankings that you have for the various air cleaning systems were very close, and, in fact, the full range varied between only eight and ten % for some dozen items. Would you comment on the relative closeness in the "test scores" and whether the differences are significant or not?

MCCORMACK: That is a feature we noticed, too, and I think probably it could be, in part, a reflection of the rating system we used. I think, in retrospect, we need to use a ranking system with a bigger range of weighting factors to spread the ratings of the systems. We have some confidence in the ranking though, because of the individual assessments that each of the authors gave the system. I think it is a reflection on the ranking system, however. It should also be noted that each system was designed to work and to meet, to the extent possible, the same objectives. Hence the system differences will tend, in many criteria, to be small.

R. J. WILLIAMS: How does consideration of natural processes of attenuation relate to selection of a system? How were estimates of natural processes made?

MCCORMACK: Natural processes do help to reduce the aerosol concentration. Natural processes were assumed to be operating concurrently with the EACS. They do not influence the system selection. Removal by natural processes was estimated by using the HAA-3 computer code which accounts for both gravitational settling and wall deposition.

EVALUATION OF IN-VESSEL EMERGENCY AIR CLEANING SYSTEMS FOR AN LMFBR

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Abstract

The goal of direct application in-vessel air cleaning systems is to reduce the two hour integrated dose leaking from a containment vessel after a design basis accident by rapidly reducing airborne sodium aerosol concentration within the vessel. This reduction in concentration is achieved by direct action on the entire containment volume rather than by a more conventional recirculating clean-up loop. Strategies that have been evaluated include: increased sedimentation by enhanced agglomeration using powder dispersal, acoustic energy, or turbulence, and powder scavenging. Experiments were conducted by burning metallic sodium in a 90 m^3 chamber to achieve aerosol concentrations up to 10 gm/m^3. The time decay of the airborne mass was measured by sequential filter sampling and the effectiveness of each enhancement method was evaluated by comparison with decay profiles of untreated aerosols.

Experiments with induced turbulent agglomeration show 2-hour dose reduction factors (DRF's) up to 43. Under the same scale turbulence conditions it is likely that a similar DRF would be achieved in a 30 m high containment vessel. Powder dispersal scavenging tests in the same chamber showed 2-hour DRF's up to 7.2--a performance level which would also be duplicated in a 30 m high containment vessel.

I. Introduction

One of the safety features that might be incorporated into an LMFBR is an emergency air cleaning system (EACS) that can operate in the event of a sodium fire to reduce the concentration of airborne sodium fume and accompanying radioactive fission products in the reactor containment vessel. Rapid removal of aerosol particles will reduce the amount of radioactive material leaking from the containment vessel to the external environment at the design leakage rate of 0.1% of the total volume per 24 hours.

Three modes of operation of an EACS have received attention: gas recirculation through a gas cleaning device, excess gas pressure purged to the outside through a gas cleaning device, and direct in-vessel reduction of airborne concentrations by a system which acts on the entire containment vessel atmosphere at once. A primary figure of merit for an EACS is the "dose reduction factor" (DRF) achieved in a two hour period following start of the clean-up system:

$$\mathrm{DRF}(t_*) = \frac{C_o t_*}{\int_0^{t_*} C(t)\,dt} \qquad (1)$$

where C_o is the initial mass concentration of aerosol particles, C(t) is the mass concentration-time history of the aerosol under treatment, and t_* is a time period, taken to be 2 hours. A minimum design goal is a system with a DRF (2 hour) capability of 10 in a 30m high containment vessel. Although a DRF (2 hour) of 10 might be attainable with gas recirculation or gas purging it would require such an extremely large filtration and air flow system capacity (200,000 cfm even at 100% cleaning efficiency) that it would (1) represent a significant capital investment (2) require large amounts of power that would be difficult to obtain during an emergency following a major reactor accident and (3) occupy a large fraction of the containment volume. The third mode of operation, direct in-vessel precipitation of airborne particles, has excellent potential for rapidly reducing aerosol concentration with devices that require only a low to moderate energy input. Specific emergency air cleaning systems for LMFBR's, of both the direct and recirculating type, have been suggested and theoretically analyzed in Reference 1.

A number of possible direct in-vessel systems have been eliminated from consideration for use with sodium. In particular, liquid sprays for scavenging sodium aerosols have to be abandoned in the absence of a liquid that is safe to use with sodium metal. Foam encapsulation has similar problems of chemical incompatibility with molten sodium metal. The increased sedimentation that results from enhanced agglomeration after dispersal of inert powder into sodium aerosol can be shown on theoretical grounds to require excessive amounts of powder to achieve a DRF (2 hour) of 10, however, this approach might be used to enhance the performance of other direct systems. For similar reasons, clean up systems that require deployment of large collection surfaces are unattractive, i.e., the amount of area-intensive material required is prohibitively bulky and difficult to release rapidly.

The remaining candidate direct systems are turbulence-induced agglomeration and acoustic agglomeration to enhance sedimentation, powder dispersal scavenging, and direct electrostatic deposition. The current experimental program has focused on the first three of these systems. Each of these shows considerable promise of being adaptable to practical systems. Electrostatic precipitation in a direct cleaning mode system has not yet been evaluated by us.

II. Summary of Baseline Tests

In order to evaluate the effectiveness of the direct cleaning methods being investigated, it was necessary to establish as a baseline the aerosol evolution characteristics of an unperturbed sodium pool fire. The baseline test in our air-filled 4m high $90m^3$ rectangular chamber calls for melting and burning one pound of sodium inside an electrically heated, insulated steel pot. The relative humidity of the air-filled chamber at the start of the sodium fire was approximately 20% for all baseline fires. Sodium combustion in a normal atmosphere results in a very dense, white aerosol which in minutes fills the chamber. The mass concentration decay with time, the baseline property of most importance, was obtained with open-face absolute filter samples taken near the mid-chamber height.

Generally samples were taken over a 3 minute interval at 18.4 liters/ minute.

The baseline sodium aerosol decay rate, shown in Figure 1, was derived from data averages of eight sodium fires. Natural decay by gravitational settling gave a dose reduction factor in 2 hours of 1.45 when measured from the peak concentration point which occurs at approximately 25 minutes after the initiation of burning. This average DRF (2-hr.) value corresponds closely to the decay characteristics of stirred settling of a spherical 4 μm monodisperse aerosol particle with a true density of 1.0 gm/cm^3. Scaling up the settling of this aerosol for a 30 m high chamber, the equivalent DRF (2-hr.) would be 1.05.

The mass median diameter (MMD) and geometric standard deviation (GSD) of the baseline aerosol cloud were determined by Andersen impactor tests and found to be nearly constant with time during the settling period as shown in Figures 2 and 3. The average MMD of 4 μm, 60 minutes after the start of the fire declined to an average MMD of 3.5 μm at 350 minutes. This behavior suggests that there may be processes present that are analogous to those involved in the "self-preserving" aerosol size distribution postulated by Lai, et al.[2] For the baseline fire the GSD stayed close to 1.8 over a period of 350 minutes, as shown in Figure 3. These size measurements are fairly consistent with results from sodium pool fires conducted by Atomics International(3) (their Figures A.1.10 and A.1.11). Their GSD over the period covered by our measurements is in the range of 1.4 to 1.6 and their MMD is slightly over 3 μm for several hundred minutes. The larger MMD and GSD found by us can be accounted for by the higher effective cut-off diameters which were assigned to each Andersen stage in our sampling, following the updated and improved values published by Rao.[4] The measured ratio of chamber floor to chamber wall deposits (mass per unit area) was in the range of 10 to 80. The spread was caused, in part, by uncertainty in the measurement of the very low wall deposits collected on filter papers.

The baseline sodium aerosol was also sampled with an aerosol centrifuge[5] which fractionates particles according to aerodynamic diameter. Centrifuge data from a number of runs gave an average MMD close to 2.0 μm and an average GSD close to 1.65. The lower MMD determined by centrifuge versus that obtained from the Andersen impactor might be due to size selective losses at the aerosol inlet. Aerodynamic size calibration of the centrifuge was performed with polystyrene latex spheres of known size and density. These give reliable calibration values over the size range of interest.

III. Chemical Composition of the Aerosol

Chemical and physical tests were performed to determine the composition of some of the filter samples. Sodium deposit measurements by atomic absorption spectrophotometry indicated high ratios of total sample mass to sodium mass. These ratios were often much larger than would be associated with a nonhydrated sodium compound. The conclusion was that most of the sodium compounds on the filter sample (see Table 1) are hydrated. The data suggest the presence of mixtures of the following compounds: Na_2CO_3, $Na_2CO_3 \cdot 7\ H_2O$, and $Na_2CO_3 \cdot 10\ H_2O$. Tests for sodium peroxide (Na_2O_2) indicated the presence of less than 0.5% of that compound. In tests where $\frac{1}{2}$ lb. of sodium was burned and peak total concentrations of 2 gm/m^3 were obtained, almost all the non-water fraction of each filter deposit consisted of Na_2CO_3 with a negligible amount as NaOH. The air filled chamber employed for these tests contains about 55 gm CO_2. This is sufficient to produce the level of Na_2CO_3 deposits seen on our filters for total aerosol concentration of 2 gm/m^3. The reaction of carbonate formation from the initial sodium oxide and sodium superoxide combustion product is:

$$Na_2O_2 + H_2O \rightarrow 2\ NaOH + 1/2\ O_2$$

and $2NaO_2 + H_2O \rightarrow 2\ NaOH + 3/2\ O_2$

followed by,

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O$$

Theoretical analyses performed by other investigators[6] show reaction rates of only seconds for forming Na_2CO_3 from the hydroxide primary compound--a fact which makes these observations credible. Table 2 shows that with sufficient H_2O present in the air sodium hydroxide begins to form in significant quantities only when total aerosol mass concentrations exceed 2 gm/m^3, i.e. when greater than 1 lb. of sodium is burned in the 90 m^3 chamber. For 20% RH, there is ample excess water vapor contained in the chamber to produce sodium hydroxide levels significantly greater than those observed for larger than $\frac{1}{2}$ lb. sodium fires but insufficient CO_2 to yield greater than ~1.5 gm/m^3 of carbonate.

IV. Turbulent Agglomeration Tests

The first full chamber tests of a direct precipitation method involved the use of turbulence to enhance agglomeration and speed sedimentation. A large (3000 cfm) centrifugal recirculating blower placed in the center of the chamber produced increases in the DRF (2-hr.) value from 4.2 to 8.2 when it was started shortly after the peak aerosol concentration was reached. The time decay history of the first five tests is presented in Figure 4. In an effort to separate the relative effects of centrifugal air cleaning in the blower shroud from the effect of turbulence enhanced agglomeration and sedimentation, the blower was run with and without the fan shroud in place. Operation with the shroud off takes away a major surface for centrifugal deposition, though some cleaning credit must still be taken because of particle impaction on the fan blades. Removing the shroud did not greatly change the DRF (2-hr.) from shroud-on performance, as can be seen in Figure 4.

Substantially higher DRF's were obtained with turbulent agglomeration when the peak mass concentration was raised by a factor of 2 from the baseline peak value (~2gm/m^3). Higher concentrations were generated by larger quantities of sodium and by faster burning rates induced by blowing an air jet against the sodium pool surface. Figure

5 shows the mass concentration profiles of two of these tests which resulted in a DRF (2-hr.) of 28 and 43, respectively. Test R-21 was conducted with air-augmented burning of 1 lb. sodium whereas test R-22 involved air augmented burning of 3 lbs. of sodium. For both of these tests, blower turbulence began when mass concentrations in the chamber were above the baseline level. This confirms that higher initial particle number concentrations accelerated agglomeration in the expected fashion. Figure 5 shows another run with DRF (2-hr.) greater than 8 in which turbulence was initiated after the mass concentration had peaked and then dropped back to 2 gm/m^3. The high DRF (2-hr.) as shown by curve R-20 of Figure 5 is a result of longer agglomeration time which produced a larger MMD aerosol by the time the blower was started.

Blower induced turbulence caused agglomeration to proceed rapidly. Large visible particles, of the order of 100 µm or more, were seen uniformly deposited on horizontal surfaces near chamber view ports. It is difficult to determine whether most of the agglomeration occurs in the strong velocity gradients near the fan wheel or whether induced turbulence in other parts of the chamber causes most of the agglomeration. The particle size distribution, as measured by an Andersen impactor, shows a definite decrease in MMD with time when the aerosol is vigorously stirred and the large agglomerates settle in the chamber as shown by the sloping curves in Figure 2, however there was no clear trend in GSD. That the MMD should decrease with time is not surprising, because turbulent agglomeration and sedimentation can deplete the largest particles rapidly.

These turbulence tests demonstrate that DRF (2-hr.) values in excess of 10 are readily achievable for vessels 4 meters in height. Scale-up to containment vessel dimensions might well yield DRF's of the same magnitude as the present tests, provided the same level of turbulence can be induced throughout the larger volume. This assumes that the turbulent agglomeration process would produce substantial numbers of particles in excess of 100 µm in a matter of minutes, a process which we believe has been observed in our tests. It is likely that these large particles produce a further benefit by scavenging smaller particles as they fall through the aerosol cloud. The lower limit DRF (2-hr.) for scale-up to a 30 m chamber can be found by imagining filling the 30 m vessel with a monodisperse aerosol of diameter sufficient to produce the measured DRF (2-hr.) in the 4 m high chamber. For example a DRF (2-hr.) of 43 in the small chamber would scale to a DRF (2-hr.) of 5 in the 30 m vessel.

V. Powder Scavenging Tests

In an effort to test the scavenging capacity of various powders on the sodium aerosol, we constructed a centrally mounted overhead dust spreader in the 90 m^3 test chamber. The dust dispersal device consists of a horizontal 16" diameter plastic disc rotated at 2000 rpm by an electric motor mounted below it. Powder is dropped through a hole in the chamber ceiling onto the center of the disc and is then spread by rotational action about the chamber.

Our initial tests have employed crushed limestone (intended originally for agricultural use) which has a very low sodium content (<1 ppm). The low sodium level in this powder permits analysis of the sodium aerosol particles on the filter samples by atomic absorption spectrophotometry without chemical interference from the scavenger dust. We recognize that carbonates are widely used for suppression of sodium fires. During powder dispersal in a sodium aerosol cloud, the total mass on sampling filters rises considerably above the expected baseline level but the total sodium in the samples steadily declines as long as powder is injected.

Tests R-25 and R-26, shown in Figures 6 and 7 demonstrate the cleaning effect of limestone powders when applied to the sodium aerosol in the manner described. The crushed limestone used in both tests had an MMD of 200 μm and a GSD of 1.5. The measured total mass concentration, limestone plus sodium aerosol, is seen to rise above the normal baseline concentration during spreading. Not all the limestone particles are represented in the total mass concentration because of very inefficient capture of these large scavenging limestone particles by the sampling system. The concentrations for sodium aerosols alone, shown in Figures 6 and 7, were obtained by scaling spectrophotometrically measured sodium mass collected on each filter by the same constant of proportionality required to raise the initial pre-limestone injection sodium mass samples up to the measured total mass concentration.

In test, R-25, powder was dispersed at the maximum feed rate of 1.5 kg/minute for 21.5 minutes. The slope of the sodium concentration decay curve during this interval indicates a DRF (2-hr.) of 6.0. In test R-26, powder was dispersed at the rate of 0.13 kg/min. for 36 minutes and was then boosted to 1.5 kg/min. for the next 60 minutes. The DRF (2-hr.) associated with the slopes of the different dispersal rate segments were 4.1 and 7.2 respectively. These data show that under similar dispersal conditions in a 30 m high containment vessel, identical, if not better, DRF's would be achieved. This is because 200 μm particles can fall 30 meters in a matter of seconds. After they have fallen below the initial 4 m for which we have data, they still retain their initial unit scavenging efficiency, perhaps enhanced by the accumulated sodium aerosol coating.

VI. Acoustic Agglomeration Tests Planned

Reviews of the literature of acoustic agglomeration[7,8] hold out great promise for this mechanism to be applied as a direct in-vessel air cleaning system. The bulk of sonic agglomeration research and literature has dealt with setting up finite amplitude standing waves in precisely tuned chambers. This approach to sonic air cleaning would not be applicable as a direct cleaning method within the very large and irregularly shaped containment vessel. Recently, Scott[8] has stated that progressive saw-tooth waveforms, generated, for example, by a pulse-jet engine, would agglomerate a wider size spectrum of aerosol particles than would a tuned, standing wave system. The progressive wave idea would eliminate the problem of setting up a tuned standing wave pattern within a large vessel. An acoustic agglomeration system may also be useful as an aerosol preconditioner for other direct cleaning methods such as the scavenging system described above, even if it were found to be ineffective as a direct air cleaning method.

We have obtained and tested a (4.5 lb. thrust) Dyna-Jet pulse jet engine which burns a gasoline-air mixture and operates at roughly 250 Hz. The device is normally used to propel model aircraft. Preliminary indications are that this engine can produce sound intensities exceeding 150 dB in a localized area, a level capable of initiating sonic agglomeration phenomena. We plan to run the engine in a duct separated from the test cell atmosphere by an acoustically transparent foil membrane. The sound will be directed at the burning sodium pool to discover to what extent the anticipated rapid agglomeration of the aerosol can reduce mass concentrations through enhanced sedimentation.

VII. Conclusions

It has been demonstrated that at least two direct air cleaning systems, turbulence-induced agglomeration and powder dispersal scavenging, have an immediate prospect of satisfying a requirement for a DRF (2-hr.) equal to or in excess of 10. Acoustic agglomeration in an untuned system has good experimental and theoretical potential to serve as an aerosol preconditioning mechanism for either of these cleaning systems. Combinations of any two or more systems appear to be attractive options which should be tested by continuing research.

VII. Acknowledgement

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Table 1 Average Ratio of Total Filter Deposit Mass to Sodium Mass During Several 1 lb. Baseline Tests.

Run	M_{tot}/M_{Na}	% of Deposit Mass Assumed to be H_2O if Primary Compound is Na_2CO_3
R-12	4.6	48
R-13	3.7	32
	Theoretical Values for Pure Compounds	
Na_2CO_3	2.30	0
$Na_2CO_3 \cdot 7H_2O$	5.04	54
$Na_2CO_3 \cdot 10H_2O$	6.22	63

Table 2 Composition of the Non-Water Fraction of Filter Samples for a 4 lb. Sodium Fire in a 90 m^3 Chamber Filled with Air at 20% R.H.

Time Interval for Averaging Samples (minutes)	Total Mass Concentration Range During Sampling Period (gm/m^3)	NaOH (%)	Na_2O_2 (%)	Na_2CO_3 (%)
11 - 24	1.05 - 2.45	6	2	92
80 - 113	4.31 - 3.69	53	3	44
130 - 140	2.17 - 2.01	46	1	53

FIGURE 1

BASELINE CONCENTRATION DECAY PROFILE FOR 1.0 LB. SODIUM FIRES IN 90 M^3 AIR-FILLED CHAMBER

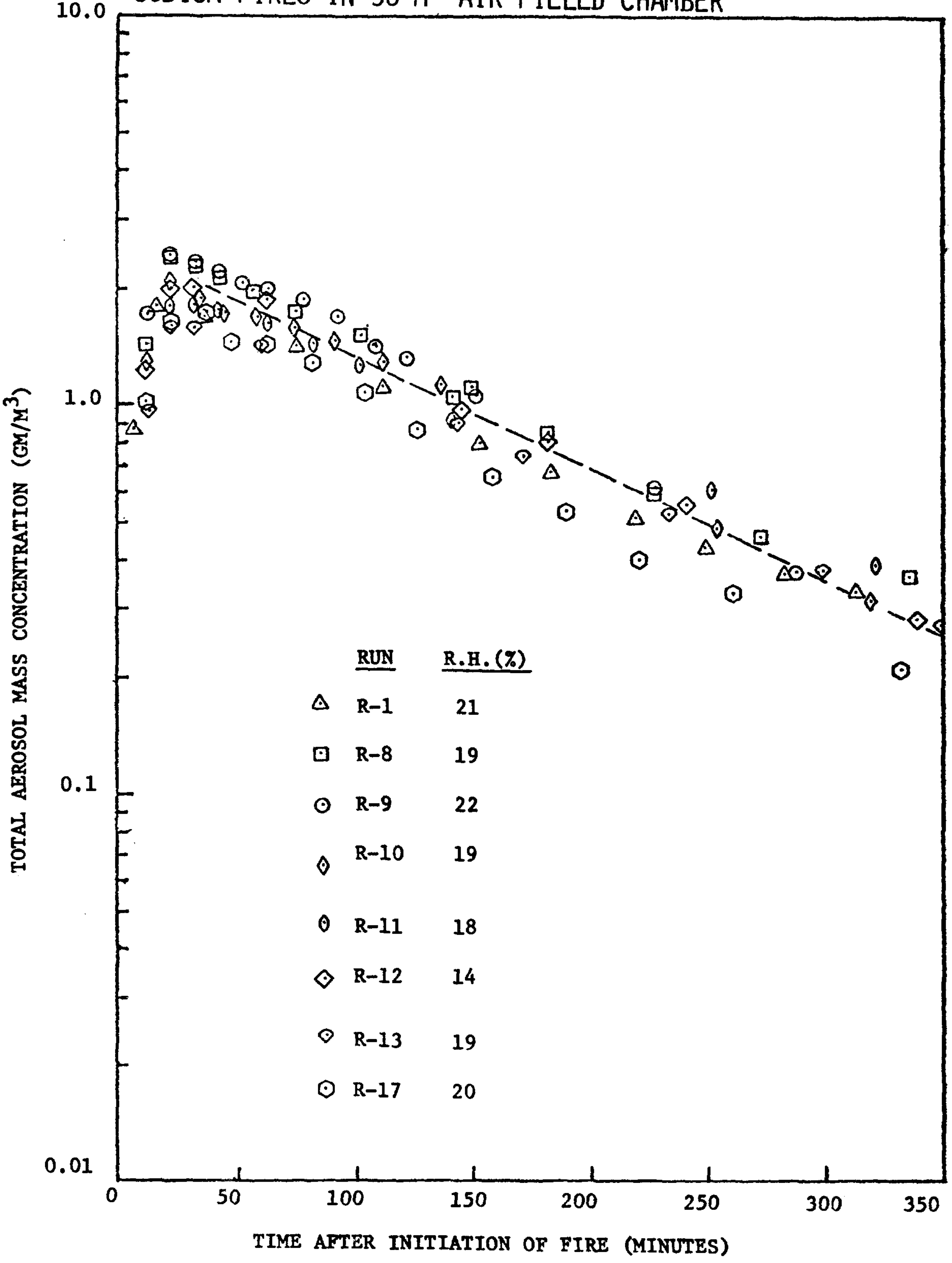


FIGURE 2.

ANDERSEN IMPACTOR MASS MEDIAN DIAMETER FOR 1.0 LB. BASELINE SODIUM FIRES AND SEVERAL INDUCED TURBULENCE TESTS

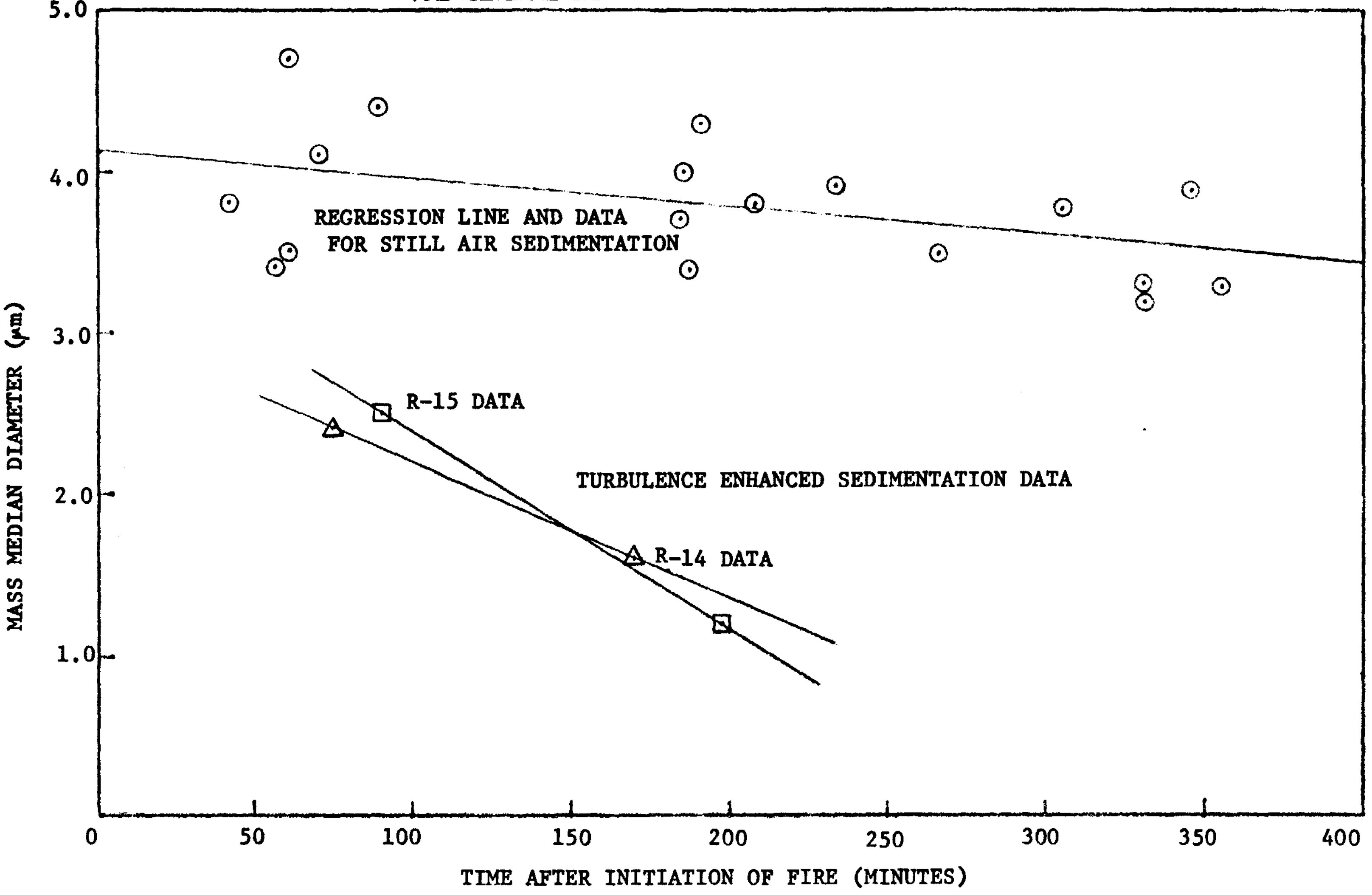


FIGURE 3.

ANDERSEN IMPACTOR GEOMETRIC STANDARD DEVIATION FOR 1.0 LB. BASELINE SODIUM FIRES

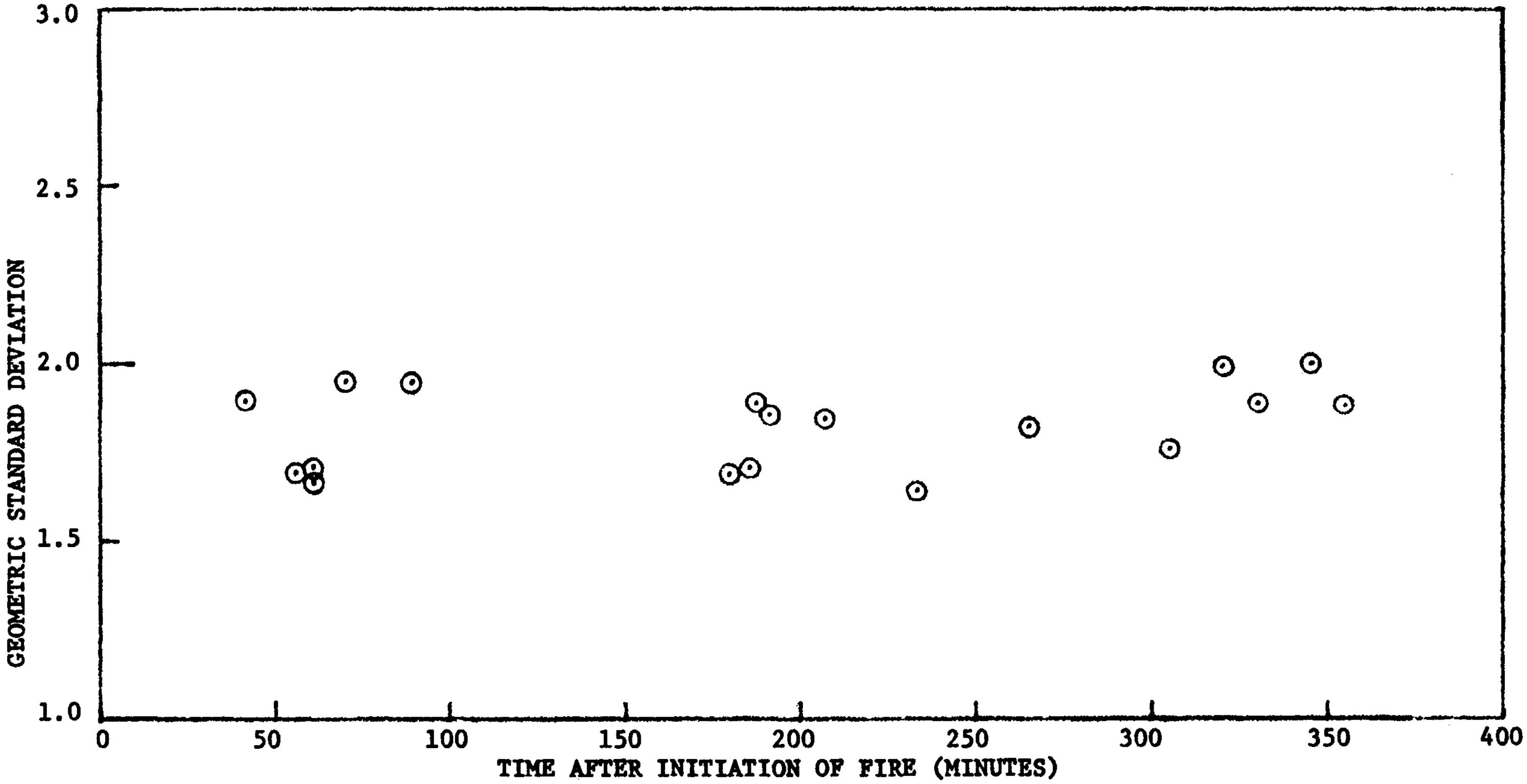


FIGURE 4.

TURBULENT AGGLOMERATION AEROSOL CLEARANCE TESTS (LOW CONC.)

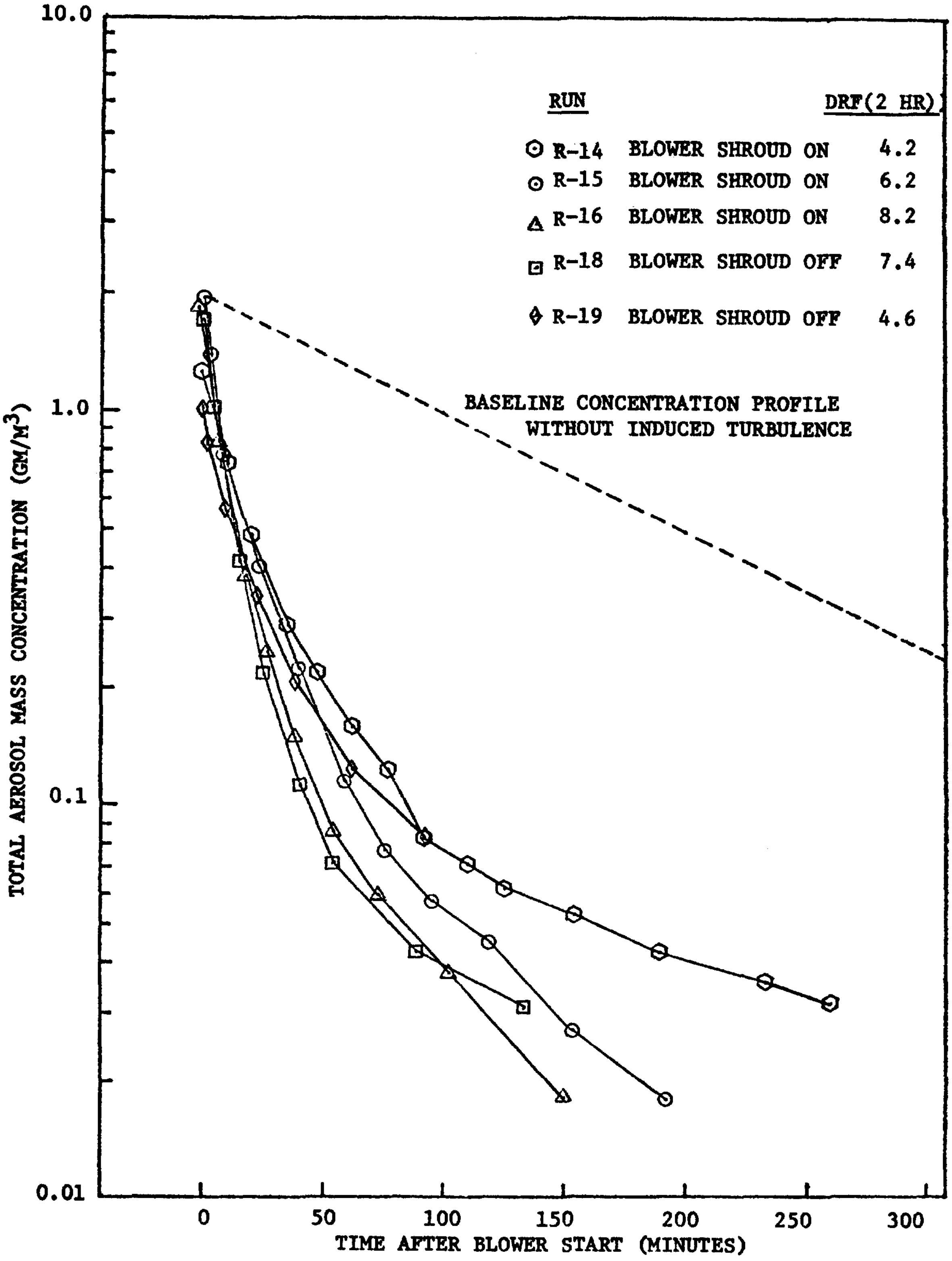


FIGURE 5.

TURBULENT AGGLOMERATION TESTS AT HIGH AEROSOL CONCENTRATION

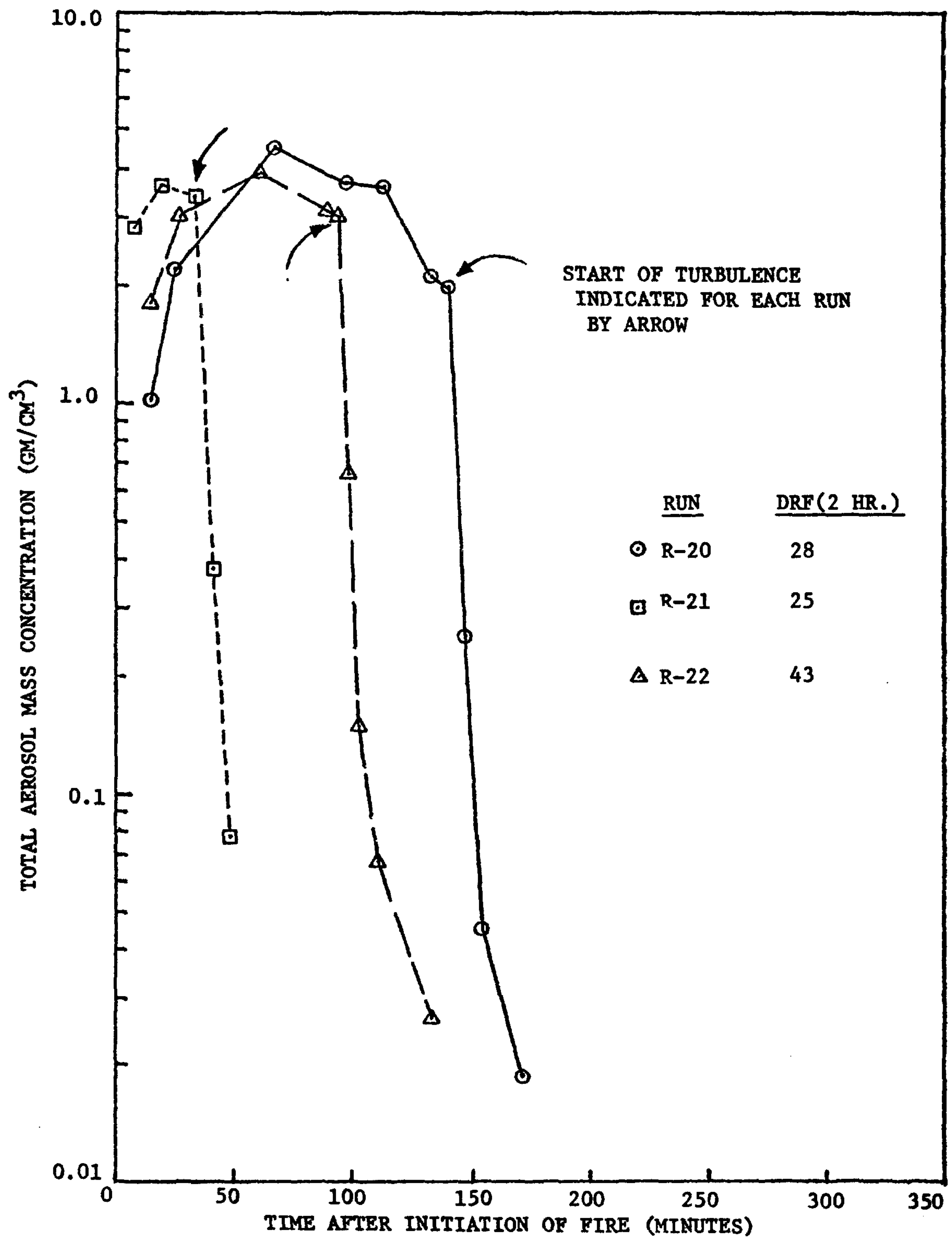


FIGURE 6.

CRUSHED LIMESTONE POWDER DISPERSAL TEST NUMBER R-25

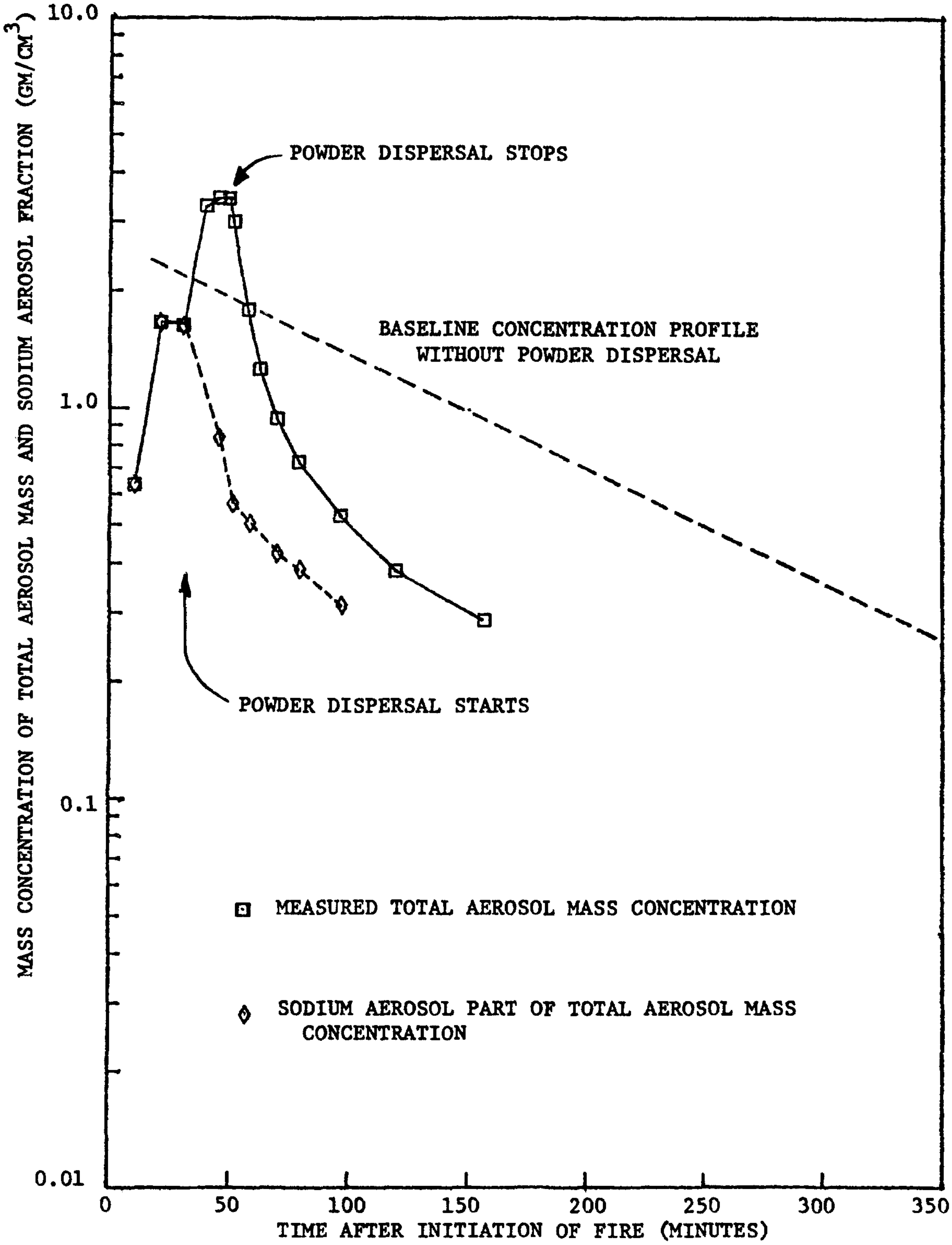
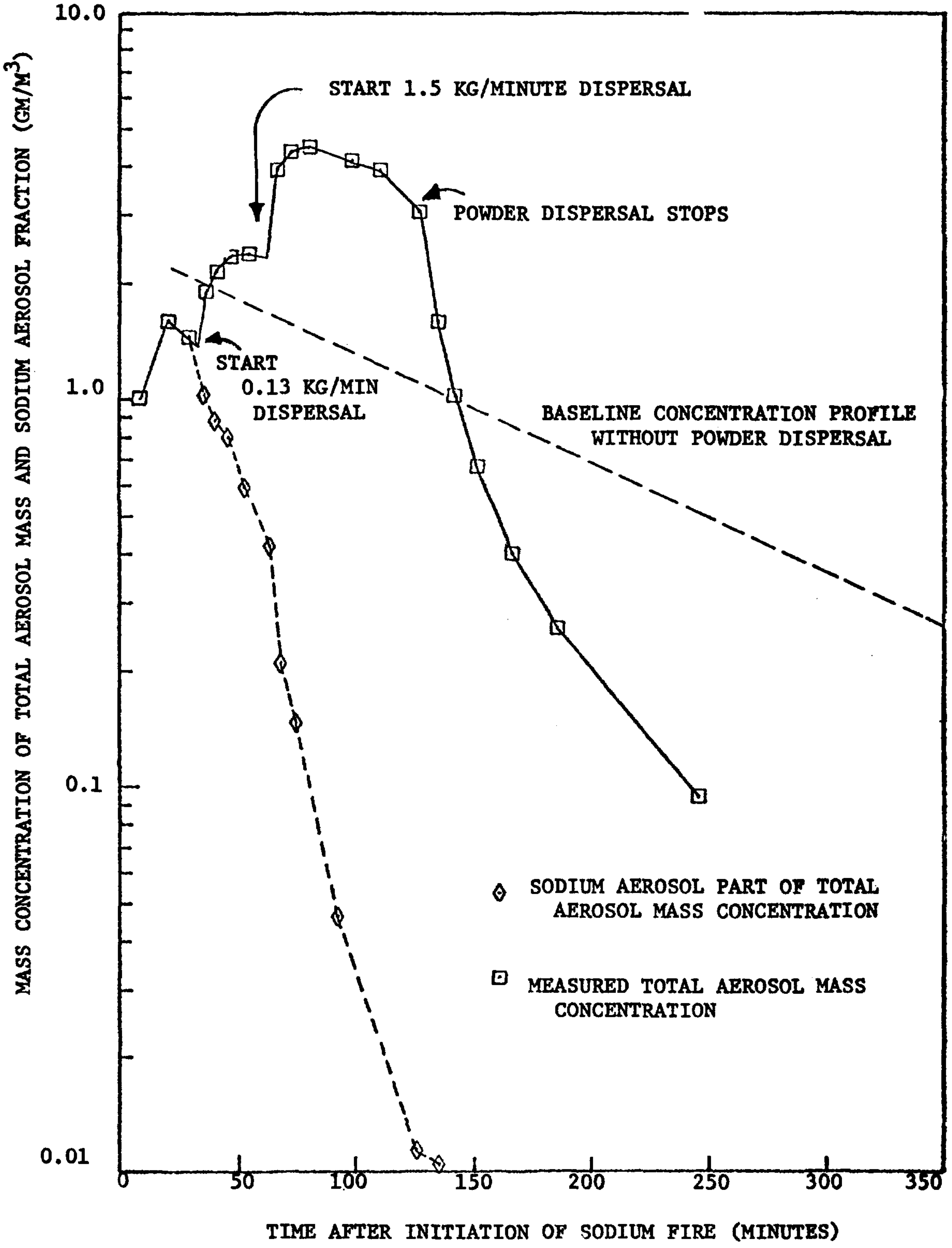


FIGURE 7.

CRUSHED LIMESTONE POWDER DISPERSAL TEST NUMBER R-26



DISCUSSION

SCHIKARSKI: I'd like to congratulate you on these fine experiments. I see the problem of extrapolation to real containment size for both the concentration decay curve and the turbulence producing equipment. Do you subtract the natural convection effect, which of course, is large already? What is the remaining effect of artificial turbulence?

HINDS: This is a preliminary feasibility evaluation to see whether the concept is valid. I'm not giving any consideration to implementation. There are many ways of inducing turbulence. If we can show that it seems reasonable, we can then consider the engineering problems of how to scale up the equipment to extrapolate our information in the case of powder scavenging, the time to fall to the vessel floor is just a few seconds. We'd expect that this effect would be comparable in a containment vessel with only small differences from our chamber. Similarly, for coagulation by turbulence, we generated micrometer particles that were coagulated by turbulence and these would, also, fall very rapidly.

SCHIKARSKI: Is it your favorite method?

HINDS: It appears to have some advantages in that it gets better and better the higher the concentration.

SCHIKARSKI: Did you revise the estimates to account for natural aerosol attenuation?

HINDS: No, we did not. We considered each method of clean-up all by itself. We did not subtract natural attenuation. However, the "DRF - 2 hour" value is the ratio of the induced attenuation to natural attenuation in every case.

LORENZ: With your turbulent agglomeration, how much improvement was a result of increased plateout on the walls of the vessel?

HINDS: When we had the outlet of the blower housing directed at the ceiling, we did not see a buildup of the material on either the exhaust housing or the ceiling. We made some rough measurements of wall deposition. Wall deposition from induced turbulence was not greatly increased over natural settling.

C. T. NELSON: What is your reason for selecting a relative humidity of 20 per cent for the baseline tests? Would not a relative humidity of 40 to 50 per cent be more representative? If tests were conducted at higher humidities, would not the chemical composition of the aerosol be different than as presented in your paper?

HINDS: We selected 20% relative humidity because it is relatively dry. We intent to conduct tests at higher humidity in the future. Regarding the second question on chemical composition, I think you are correct. The chemical composition will be sodium hydroxide for high humidities. When we ran other kinds of tests at high humidity, we believe we had a liquid droplet aerosol, whereas we had solid sodium carbonate particles at the lower relative humidity. If we do not exceed a specific aerosol concentration in the chamber, carbon dioxide will not be completely consumed and will convert the sodium aerosol particles to sodium carbonate. For many conditions, we will have a mixture of carbonate and hydroxide.

PALMER: In your paper, you state that a minimum design goal is a system with a DRF of 10. This seems extremely low for the major type of accident considered. In fact, if a DRF of only 10 is required, one would question whether any emergency air cleaning systems need to be considered.

HINDS: These tests were pilot tests to screen different direct air cleaning methods. A 2 hour DRF of 10 was arbitrarily selected to identify those methods that had potential, with further research, for high DRF values. Bear in mind, that it is the containment vessel, with a leakage rate of 0.008% of total volume in two hours, that is the primary mechanism for reducing exposure to the public. The emergency air cleaning system is intended to reduce the amount of material leaking from the containment vessel still further.

CLOSING RAMARKS OF SESSION CHAIRMAN:

In the first paper, Dr. Schikarski presented results of some aerosol behavior experiments and compared these to predictions made using the PARDISEKO code. I conclude that the agreement is very good providing that input parameters to the code are properly selected. I would note that the aerosol concentrations were low in the experiments and that no sodium or sodium compound aerosols were used.

In the second paper, Mr. McCormack presented results of a conceptual evaluation of a number of widely differing air cleaning concepts. Several of the concepts look promising. In future ERDA-sponsored research, we intend to test selected concepts; first on a laboratory scale and finally on an engineering scale.

In the third and last paper, Dr. Hinds summarized results of experiments in which the effects of turbulent-induced agglomeration and powder dispersal were determined. These results, while preliminary, look extremely encouraging. If confirmed by future experiments, such systems may result in substantial attenuation of radioactive aerosols in a containment.

In conclusion, I would say that we do not yet have a proven system for LMFBR emergency containment air cleaning. We have identified a number of concepts that look very promising, and we are proceeding to verify their performance.