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INTRODUCTION AND SUMMARY

This paper reviews results of a Stone & Webster Engineering Corporation (SWEC) assessment of the radiological consequences of postulated nuclear power plant accidents. This assessment is based on studies of accident consequences, not accident probabilities. The probability that severe core damage accidents will occur is extremely low and this fact should not be forgotten in reviewing these and other results of accident consequence analysis.

Data are presented for a core meltdown accident at a large pressurized water reactor (PWR) power plant. The radiological consequences reported, however, are for conditions applicable to a boiling water reactor (BWR) plant, as well.

The most important part of analyses of nuclear power plant accidents is the source term which defines the amount, type, and timing of the release of radioactive material to the environment. The data reported, herein, result from use of a proposed, realistically conservative interim source term. These data are compared with data derived from use of the source term employed in the NRC-sponsored Reactor Safety Study (RSS).[1]

The studies summarized, herein, show that:

- Time is a major determinant of consequences (i.e., realistic assumptions about the time at which radioactive material is released result in lower consequences than those reported in studies based on hypothetical releases very early during accident sequences).

- Fission product radioiodine will emerge at the coolant system break location in a variety of physical and chemical forms, but predominantly in the chemically reduced state of metal iodides, principally cesium iodide which is more soluble in water than table salt. An ample supply of water is available to react with these iodide salts in light water reactor accidents, including the water which remains airborne in the vicinity of the coolant system break during the period of time over which core degradation and radioiodine release are postulated to occur. The radioiodine portion of the source term can be shown to be far lower than that employed in studies such as the RSS and more recent studies employing similarly large source terms.

  The behavior of particulate radioactive material released in the form of aerosols (i.e., agglomeration, settling, etc.) is such that the airborne concentration is only a small fraction of that previously postulated to be available for release to the environment. The aerosol behavior data reported herein address only the aerosol depletion in the vicinity of the postulated coolant system break. When these depletion effects are combined with other aerosol depletion mechanisms, such as those operable within the reactor coolant system, the particulate portion of the source term can be shown to be far lower than the quantities assumed in the RSS.

- An accident involving a coolant system break outside the containment building is not a "dry accident" as some have claimed but, in fact, is a very wet accident (i.e., it could be characterized as a rain forest environment).

- The core meltdown accident, popularized as the China Syndrome, is not a potential catastrophe, but would be similar to other industrial accidents in terms of health effects consequences. This paper reports a conservative assessment of the radiological consequences of such an accident at a specific site. A "best estimate" analysis is expected to result in the calculation of no early fatalities and far fewer latent health effects during the thirty year latency period for such an accident at a significant number of power reactor sites.

SWEC proposes the adoption of an interim source term pending completion of confirmatory research currently in progress. The proposed interim source term compares with the source term used in the NRC's Reactor Safety Study as follows:

Radioactive Material Group	NRC Reactor Safety Study Rel. Cat. PWR-2	SWEC Proposed Interim Source Team
Noble Gases	90%	100%
Radioiodines	70%	1%
Cesium-Rubidium	50%	1%
Tellurium-Antimony	30%	1%
Barium-Strontium	6%	1%
Ruthenium	2%	1%
Lanthanum	0.4%	0.4%

SWEC has analyzed the potential health effects of a core meltdown accident at a specific nuclear power plant using both the NRC RSS source term and the proposed interim source term. The results are summarized at the top of page 3.

These results demonstrate the degree to which the RSS source term leads to unrealistically high calculations regarding health effects. The health effects calculated with the proposed interim source term, while much lower, are still conservative. Use of this interim source term will insure adequate protection of public health and safety.

SWEC invites your comments on this paper in order to help guide its future efforts in pursuing the important source term question in conjunction with others in the nuclear safety analysis community.

STONE & WEBSTER CALCULATED
POTENTIAL HEALTH EFFECTS IN A POPULATION
EXPOSED TO A 24-HOUR RELEASE
STARTING 2½ HOURS AFTER SHUTDOWN*

	NRC Reactor Safety Study Source Term	SWEC Proposed Interim Source Term
Early Fatalities		
Noble Gases	0	0
Radioiodines	2,500	0
Particulates	11,000	18
Latent Fatalities Per Year		
Noble Gases	6	8
Radioiodines	208	1
Particulates**	333	17
Latent Thyroid Cancers Per Year		
Radioiodine Inhalation	1,750	25

*Numbers are not additive
**Based on exposure to contaminated ground for seven days

BACKGROUND

It is often said that "an accident anywhere in the nuclear industry is an accident everywhere in the industry." The world-wide effects on regulatory reaction and public perceptions of risk as a result of the Three Mile Island accident in the United States, the radioactive liquid discharge at Tsuruga in Japan, and other events confirm this statement. A corollary truism could be stated as "a gross overestimate of the risks of nuclear power anywhere results in needless public concern everywhere."

Due to the absence of more substantial data, intentionally ultraconservative initial assumptions were made in the early stages of the civilian nuclear power development program regarding the potential radiological consequences of hypothetical accidents at hypothetical reactors (e.g., WASH-740 in 1957).[2] Subsequently, these early estimates were recognized as being grossly conservative and were refined in a widely referenced document, TID-14844 published in 1962, to provide conservative design bases for commercial nuclear power plant siting and licensing.[3]

The TID-14844 source term postulated release to the containment atmosphere of 100 percent of the core inventory of noble gases, 50 percent of the radioiodines, and 1 percent of the remainder in particulate form. The 50 percent radioiodine portion of the source term was divided: 25 percent was assumed to be airborne in the containment and 25 percent was assumed to be plated out on surfaces or dissolved in water. Subsequently, design basis source terms were delineated in the form of safety guides (later relabeled regulatory guides).[4,5] These regulatory guides assumed that the chemical composition of the 25 percent airborne radioiodines was 91 percent elemental iodine (I_2), 4 percent methyl iodide, and 5 percent in particulate form.

These regulatory guide source terms were combined with design basis data, such as a containment leak rate of approximately 0.1 percent of the containment volume per day. They were intended for regulatory use for accidents other than the Class IX accidents, such as core meltdown accidents. The Class IX accidents were relegated to a special status due to the extremely low probability of their occurrence. This class of accidents has been studied extensively in the probabilistic risk assessment (PRA) area.

The first major effort at a quantitative probabilistic assessment of the risks of nuclear power was reported in the Reactor Safety Study (RSS).[1] Subsequently, a similar PRA study, Phase A of the German Risk Study (DRS), was completed in the Federal Republic of Germany.[6] Although these studies provide valuable perspectives on the probabilities of the occurrence of specific events, they include analyses of the public consequences of these events that, unfortunately, are exaggerated due to the use of ultraconservative source terms and dose assessment methodologies.

At the conclusion of its investigations into the accident at Three Mile Island (TMI), the Kemeny Commission reported that virtually no appreciable quantity of airborne radioiodines and particulates existed in the containment building.[7] (Recent television pictures from TMI show

that this phenomenon existed despite the reduction of the top 5 feet of the core to rubble.) This low amount of airborne material actually experienced is not an isolated instance, but is in accordance with the results ~~of~~ other accidents and experiments. Although more than 10 million curies of noble gases were released into the TMI containment building, only about 20 curies of radioactive iodines escaped. This occured despite the fact that the activity of the iodine inventory in a reactor core is about the same order of magnitude as the activity of the noble gas inventory. Similarly, very little of the available core inventory of particulate radionuclides was present in the containment atmosphere. These findings are consistent with other reactor accident experiences as well (e.g., the SL-1 accident in 1961, in which only about 20 curies of iodines were released out of an inventory of 28,000 curies and other particulate radioisotopes were released in only negligible amounts).

Following the Kemeny Commission report, three nationally recognized scientists sent a letter to the Chairman of the Nuclear Regulatory Commission (NRC) calling for adoption of a more realistic source term.[8] The American Nuclear Society published a collection of articles on the subject of source term in the May 1981 issue of Nuclear Technology.[9]

The iodine release question was also addressed by the Nuclear Safety Oversight Committee in a 1980 letter to the President, in which it stated that "...there is evidence that the radiological consequences of some nuclear accidents may be substantially less than assumed previously... [and] if this assessment proves correct, it would have major implications for such regulatory issues as plant siting and emergency planning."[10]

Since the publication of the articles in Nuclear Technology, investigations by numerous individuals and organizations have continued, such as the research funded by the NRC, the Electric Power Research Institute (EPRI), and the Atomic Industrial Forum sponsored Industry Degraded Core-Cooling Rulemaking (IDCOR) program. Ample information is now available from these investigations to support a reduction in the radioiodine and particulate portions of the accident source term. There is now general agreement among knowledgeable reactor safety investigators and regulators that the presence of moisture in light water reactor accidents and aerosol depletion play major roles in reducing the amounts of radioiodides and particulates that are airborne and thus available for release to the offsite environment.

It is wrong to assume that the radioiodine is released in the molecular gas form (I_2) as was assumed in earlier studies. Following the natural laws of chemistry and physics, radioiodine combines with other elements, such as cesium, to form iodide salts, such as cesium iodide which is more soluble in water than table salt. The difference in the behavior of a gas and a salt is very significant; a gas can migrate over large distances, whereas a salt dissolves readily in water and remains there with some minor partitioning of gaseous iodine over long periods.

The laws of chemistry and physics also act to mitigate the release of aerosols during nuclear power plant accidents. It takes very little time for aerosol dynamics to result in agglomeration and settling out of

aerosols near any break in a reactor system. Considering the large masses of materials, the presence of large quantities of water, and many other aspects of reactor plants, a large release of iodine or aerosols to the environment cannot be reasonably postulated to exist in a nuclear power plant reactor accident.

Recent analyses conducted at the Karlsruhe Nuclear Research Center in Germany by the Project for Nuclear Safety (PNS) demonstrate much lower radioiodine and particulate source terms than were reported in the German Phase A DRS (i.e., less than 1 percent of the core inventory of radioiodines and particulates as shown in Table 1).[11]

Recent work at the Oak Ridge National Laboratory (ORNL) reported by Parker demonstrates that a significantly large fraction of metallic fission products, such as the radiologically significant ruthenium and tellurium, are scavenged by molten steel or by the zirconium-silver alloy and are retained in the melt in a core melt accident without escaping from the immediate vicinity of the core material.[12]

Dr. Walton Rodger, in the American Institute of Chemcial Engineers' 1981 Robert E. Wilson Memorial Lecture, summarized the issues involved and suggested overall source term reduction factors of 100 for cesium, iodine, and tellurium and 1000 for all other radioisotopes for a core melt accident. Much larger reduction factors are recommended by Rodger for other severe core damage accidents.[13]

It is reasonable to conclude from the published literature that (1) a high percentage of noble gases will be released to the containment during severe core damage accidents, (2) essentially all of the radioiodine inventory will be released from the fuel, but will react with other elements (principally cesium) to produce soluble iodides which will not be available for release to the environment in any large quantities, and (3) particulate fission products would be released as a dense aerosol which would quickly settle out in the reactor coolant system and in the immediate vicinity of the break in the coolant system, with natural agglomeration and settling processes being enhanced by the presence of moisture. The data reported in this paper support these conclusions and extend the investigations into the assessment of the radiological consequences off site.

ACCIDENT CATEGORIES AND SOURCE TERMS FOR ANALYSIS

Postulated nuclear power plant accidents involving severely degraded core conditions can be divided into two types: (a) those resulting in release of fission products into the reactor containment building, and (b) those resulting in bypass of the containment. Each category is discussed briefly below.

Release Into Containment Building

Accident scenarios involving releases of significant amounts of fission products into the containment building can be postulated to occur under two conditions, namely: (a) those accidents in which the reactor coolant system pressure boundary is breached inside the containment (i.e., large or small break LOCA) and during which the reactor pressure vessel remains intact (TMI is an example of such an accident), or (b) those accidents in which a core melt-through of the reactor pressure vessel occurs.

In the first instance, the containment structure could reasonably be postulated to prevent release to the environment, and all of the natural forces would have adequate time to reduce substantially the concentrations of radioiodines and particulates in the containment atmosphere by several orders of magnitude (even without operation of active safety systems such as containment sprays).

In the second instance, where a core meltdown is postulated to occur causing melt-through of the reactor pressure vessel, the pathway of fission products into the containment would be different; however, the concentration of radioiodines and particulates in the containment atmosphere may not be appreciably different from the first category. Under the conditions of this more severe accident, the time prior to postulated release from the containment is a major factor to be considered. In the Reactor Safety Study (RSS), the earliest time for release of radioactivity to the environment was 2½ hours after shutdown of the reactor. This paper adopts a similar time for the start of a release.

Containment failure of a severity which could rapidly release a large fraction of the airborne material is highly improbable. The increase of pressure following a reactor system rupture and core damage, even if not limited by core spray and the heat sink effect of the structures and equipment, would realistically be expected to do no more than cause a localized break, as at a containment penetration which would then limit both rate of increase of pressure and final pressure so as to preclude a larger failure. The safety factor and details of design are, of course, such that even a localized break is improbable. Nevertheless, results are presented on a sensitivity basis and related to various times prior to release to the environment and various time periods during which release is postulated.

Releases Which Bypass Containment

One major accident scenario has been identified that could result in a substantial release of fission products bypassing the containment: the so-called V sequence from the RSS. In this sequence, the reactor coolant water is postulated to be blown down outside containment due to assumed valve failures in the safety injection systems connected to the reactor coolant system. It was an extremely low probability event in the RSS and has been made even less probable in United States light water reactor plants due to recently imposed operational regulatory requirements.[14]

We have analyzed this sequence, and some of the analysis results are presented in this paper. Although several investigators have described this sequence as a "dry accident," our analyses clearly demonstrate that it is a wet accident. The difference between a dry accident and a wet accident is significant because the moisture that is present at the postulated break location outside containment has a substantial effect in reducing airborne concentrations of radioiodine and aerosols before they can escape to the environment.

Source Terms for Release to Environment

Table 1 presents a comparison of the source terms used in the RSS, the German Risk Study (DRS), the recent German Project for Nuclear Safety (PNS) Study, Regulatory Guides 1.3 and 1.4, and the interim source term proposed by SWEC in this paper.

The interim source term proposed by SWEC represents the following reductions in comparision with the RSS:

	RSS Release Category PWR-2	Proposed Interim Source Term	Reduction Factor
Noble Gases	90%	100%	Slight increase
Radioiodine	70%	1%	70
Cesium-Rubidium	50%	1%	50
Tellurium-Antimony	30%	1%	30
Barium-Strontium	6%	1%	6
Ruthenium	2%	1%	2
Lanthanum	0.4%	0.4%	*

*The conservative 0.4% release for this group of isotopes in the RSS is unchanged in the proposed interim source term.

Table 2 lists the major natural mechanisms which affect the release of fission products. Taken together, these mechanisms result in far greater reductions than those shown above for the proposed interim source terms. However, pending completion of confirmatory research presently being performed on the effects of these various mechanisms, the proposed source

term intentionally represents a reasonably conservative interim basis for assessment of the radiological consequences of postulated nuclear power plant accidents.

The various effects delineated in Table 2 act to reduce the quantity of fission products released to the environment. This paper presents data on the following aspects of these reductions: (a) the airborne moisture in the vicinity of the break, (b) the aerosol concentration reductions in containment for a large LOCA, and (c) the aerosol concentration reduction in the building outside containment in which the V sequence pipe break is postulated to occur.

The aerosol reduction effects reported herein are over and above the reductions which occur in the core, the reactor pressure vessel, and the coolant system piping. Taken together, these effects are extremely large, making the proposed interim one percent radioiodine and one percent particulate source term a conservative statement of the quantity available for release to the environment.

In addition to the quantity and type of radioactive material, time is a very important part of the application of the source term. In this paper, the postulated releases to the environment are analyzed as a function of time prior to release from containment and the period of time during which the release occurs.

ANALYSES

Aerosol Concentrations in Containment Atmospheres

The behavior of aerosols in containment atmospheres is addressed by Morewitz, Parker, Creek, and Bunz in Nuclear Technology.[9] It is also addressed in NUREG-0772.[15] In the analyses presented herein, aerosol concentrations have been calculated as a function of time for a large PWR containment.

Figure 1 depicts the calculated pressure and temperature as a function of time after a large break LOCA event. In this analysis, full Emergency Core Cooling System (ECCS) flow is initiated. This assumption results in very early depletion of the Refueling Water Storage Tank (RWST) inventory (450,000 gallons in this analysis). At an ECCS flow of 5,000 gpm, the RWST inventory is depleted in approximately 1½ hours. It is further assumed that the ECCS fails to switch over to the recirculation mode, resulting in loss of core cooling after RWST depletion. In addition, the analyses were made conservative by assuming that operation of the containment spray system was not initiated. This has the effect of maximizing containment pressure and temperature. The steam density in the containment under these conditions is shown in Figure 2. It can be seen that, even without initiation of the containment sprays, the containment atmosphere is saturated at the time of RWST depletion.

Figure 3 presents calculated airborne aerosol concentrations in the containment as a function of time. The aerosol data are calculated with the HAA-3B computer program.[16] Results are presented for release of aerosols into the containment over periods of 15, 30, and 60 minutes. The aerosol particle size distribution in these analyses is log normal. The correlation between particle size and aerosol concentration in the containment atmosphere is consistent with that reported by Postma and Hilliard.[17] A total aerosol amount of 1,000 kg is assumed to be released into a containment with a volume of 1.9×10^6 ft^3 (54,000 m^3).

The effect of containment sprays is not included in these analyses. If it were, the aerosol concentration would be essentially eliminated. The major effects of aerosol retention inside the reactor pressure vessel, its internals, and the reactor coolant system are also not treated explicitly in these analyses. The analyses are intended to show the effect of the calculated containment environment in reducing aerosol concentrations. This effect is over and above the other effects mentioned above. These other factors are extremely important in determining how much aerosol material is released in the first place.

As noted earlier, the aerosol behavior analyses are presented to show only a portion of the natural phenomenological effects which support a one percent particulate source term as being conservative.

Analysis of Atmospheric Environment at V Sequence Break Location

For the postulated break in the low-pressure piping outside containment in a V-sequence event, analyses were performed using a combination of standard small break LOCA (6-inch break) analyses results in combination with thermal hydraulic analyses and the HAA-3B aerosol program.

The chronology of events for the small break LOCA is presented in Table 3. One of the important parameters for the present analysis is the time of depletion of the RWST. The contents of a 450,000 gallon RWST would be depleted in 1½ hours if there were no operator action taken to reduce ECCS flow. However, if the operators secure the low head safety injection pumps 30 minutes after the break occurs, the RWST depletion time is extended to 15 hours. The reactor coolant pressure is higher than the shutoff head of the low head safety injection pumps. The flow of water from the low head pumps is unaffected by the break size. Thus, the 1½ and 15 hour time periods apply to a 3-inch, 4-inch, or 6-inch break.

The resulting calculated environment in a room of a typical auxiliary building, with a volume of 193,000 ft^3, is presented in the following figures. Figure 4 presents the calculated temperature and pressure as a function of time. It is assumed that a 10 foot by 12 foot internal wall collapses, producing a 120 ft^3 opening as a result of the pressure effect. The pressure is atmospheric after this opening occurs. Approximately ¼ hour after the break occurs, the temperature rises sharply in the vicinity of the break. This is due to the change in the quality of the blowdown from a two-phase steam-water mixture to steam entering the room. After RWST depletion, at approximately 1½ hours, the temperature decreases to the saturation level of 212°F. The calculated steam density in the vicinity of the postulated break is presented in Figure 5.

At approximately 3½ hours after the break occurs, steam flow out of the room is calculated to end and air inflow begins as the steam condenses.

The core is postulated to degrade, resulting in the release of fission products, during the one-hour period following core uncovery (i.e., 1½ to 2½ hours after the break occurs for the earliest possible RWST depletion time).

It is significant to note that the building atmosphere in the vicinity of the postulated V-sequence break remains saturated for a least 3½ hours after the break (after this time, air inleakage would occur for some period of time). Thus, steam is available at the break location to greatly reduce the amount of airborne radioidines and particulates. Therefore, the V-sequence has been improperly characterized as a "dry accident." Rather, the atmosphere in the vicinity of the break may be described as a rain forest.

Figure 6 presents results of analyses of aerosol concentrations in this volume as a function of time for 15, 30, and 60 minute aerosol release periods. The aerosol input parameters were the same as those for the containment analyses presented in Figure 3. For the 60 minute aerosol

release period, the aerosol concentration can be seen to be reduced by a factor of 38 during the 2 hour time period from termination of aerosol release out of the break (2½ hours in Figure 6) to 4½ hours after the postulated break occurs (i.e., from 38 to 1 g/m^3). For the 15 minute and 30 minute release periods, the aerosol reduction is much greater (e.g., a factor of 60 reduction for the 30 minute release case in the 1½ hour time period from termination of the aersol release).

As stated earlier, this is only one of the effects which mitigates against release of particulates in light water reactor accidents. Thus, the proposed one percent interim source term is shown to be a conservative estimate when one considers that other removal effects (discussed in Table 2) are in addition to that shown in these figures.

Analyses of Individual Doses Offsite

This section presents results of analyses, using the proposed SWEC source term, of doses received by individuals off the site under what may be described as very conservative conditions. So-called "best estimate" analyses would result in far lower calculated doses. In a best estimate analysis, even lower release quantities of radioiodines and particulates would be combined with longer time periods prior to release and longer release periods.

The data in this section are presented in a unique format as a function of time prior to release and duration of release. Inherent in these data is the non-mechanistic postulation of release from containment at the specified times presented.

Analyses of doses received by individuals near the site of a postulated accident are calculated for various atmospheric release assumptions. The most important meteorological parameter used in such analyses is the term X/Q, which has units of sec/m^3. When this parameter is multiplied by the release rate Q, in units of Ci/sec, the downwind concentration is calculated in units of Ci/m^3 of air at the location of interest offsite. Figure 7 presents annual average X/Q data as a function of distance for 42 actual nuclear power plant sites in the United States. From these data, a representative site boundary X/Q of $1x10^{-5}$ sec/m^3 was selected to demonstrate the calculation of the dose to maximally exposed individuals for postulated release conditions.

Figure 8 presents the dose that would result from the whole body exposure following release of 100 percent of the available noble gas inventory reported in Table 3.2 of NUREG-0771 for a 3,560 Mw reactor at the end of a normal fuel cycle.[18] These doses were calculated with a X/Q of $1x10^{-5}$ sec/m^3 and a semi-infinite cloud model. Radioactive decay following shutdown was included prior to release and during the specified release periods. Decay during transit to the site boundary was neglected. Four curves are presented which show the dose received as a result of either a 1, 6, 24, or 72 hour release starting at a time T_R after shutdown. An example of how these curves are read is as follows: The dose for a 24 hour release starting at time T_R = 2½ hour sis approximately 160 rem.

The time of exposure is assumed to be equal to the time of release. The meteorological conditions are conservatively assumed not to change during the release periods specified in the figure. The dose conversion factors used in these analyses reflect the lifetime dose commitment following the specified exposure period (i.e., 1, 6, 24, or 72 hours).

Figure 9 presents whole body doses received by the same maximally exposed individuals due to cloud immersion and ground deposition exposure to one percent of the available radioiodine inventory released over 1, 6, 24, or 72 hour time periods as a function of T_R, the time prior to the start of the postulated releases. All other conditions are the same as for those described for Figure 8. It should be emphasized that these are whole body doses from cloud immersion and associated ground deposition of radioiodines.

The ground deposition portion of these doses are based on exposure to contaminated ground for a period of seven days and a deposition parameter (D/Q) with a value of $2x10^{-8}$ sec/m^2 as opposed to using a X/Q parameter in combination with a 0.01 m/sec deposition velocity, as was the case in the RSS. This dosimetric model is based on the methodology described in Regulatory Guide (RG) 1.109 with appropriate modifications to reflect the short release periods as opposed to continuous releases on an annual basis which is the case in RG 1.109.[19]

Figure 10 presents whole body doses from a release of one percent of the remaining radionuclides--i.e., those not included in the noble gas or iodine categories. These radionuclides are treated as particulates. The dosimetric modeling of RG 1.109 was employed in these analyses, with appropriate modifications to reflect the short release periods. Due to the relatively long half-life of the particulate radionuclides, the dose is essentially the same whether the release is postulated to occur over a 1, 6, 24, or 72 hour period. Thus, Figure 10 presents a single dose curve for these release periods as a function of exposure time, T_E, to the particulate deposits on the ground. These data reflect no evacuation, sheltering, or cleanup.

In addition to the effects of time depicted in Figures 8 through 10, increased distance from the reactor has a marked effect on dose. The cloud immersion and inhalation doses decrease roughly in proportion to the curves presented in Figure 7, i.e., the dose decreases with decreasing X/Q. This Gaussian model provides a reasonable first approximation. Over longer time periods, plume meander and other meteorological effects become important. As an indication of the decrease in dose with distance, the following comparison is presented:

	Dose Reduction	
Distance From Reactor	Cloud Immersion and Inhalation	Ground Deposition
Site Boundary (e.g., 0.5 mi)	1.0	1.0
10 miles	1/70	1/400
50 miles	1/500	1/6,000

Analysis of Health Effects at A Specific Site

This section includes data on potential health effects at a specific site using the dose data presented in the previous section. These are not "best estimate" data but are presented more in the sense of conservative bounding conditions.

The data are for extremely low probability events postulated to result in the earliest possible release of radioactivity. They include an inherent, non-mechanistic assumption of release from containment, preceded by failure of the core cooling system to function as designed and with no operation of the containment sprays. It cannot be overemphasized that these are extremely conservative assumptions.

The potential health effects were calculated for a specific site using actual offsite population distribution data and annual joint wind frequency distribution meteorological conditions. Although the population at the selected site exceeds 3 million within a radius of 50 miles, the calculated potential health effects relate to exposure to the much smaller population residing within a few miles of the site.

The calculated number of potential early fatalities resulting from release of 100 percent of the noble gas inventory released over a 1 hour or 6 hour period as a function of time of release (T_R) after shutdown are reported in Figure 11. No potential early fatalities were calculated for release periods of 24 or 72 hours. It should be noted that no potential early fatalaties were calculated for time periods equal to or greater than the earliest postulated release of 2½ hours. That is to say, all of the dashed curve data relate to previous hypothetical, unrealistic assumptions.

No early fatalities were calculated for the release of one percent of iodine inventory, reported in Table 3.2 of NUREG-0771.

Figure 12 presents the calculated number of potential early fatalities assocated with the release of one percent of the particulates inventory over a 1, 6, 24, or 72 hour period. These data include contributions from cloud shine, inhalation, and are for an exposure period of seven days to the contaminated ground with no evacuation or other protective measures.

Figure 13 presents the calculated number of latent fatalities associated with release of 100 percent of the noble gas inventory. All potential latent fatality data presented in this paper are on a per year basis for a 30 year period. This method of reporting is consistent with that used in the RSS. Less than one latent fatality per year is calculated to result if the entire noble gas inventory is released starting approximately 100 hours after shutdown.

Similarly, Figure 14 presents the calculated number of latent fatalities associated with the cloud immersion and ground deposition from a release of one percent of the iodine inventory in the core.

The calculated numbers of potential latent fatalities associated with release of one percent of the remaining isotopic inventory in particulate form are presented in Figure 15. The method of presentation of the health effects data for the particulates is similar to that used for doses in Figure 10. The number of latent fatalities is plotted as a function of the exposure time, T_E, during which the individuals are assumed to be exposed to contaminated ground. For comparison purposes, the health effects of inhaled particulates and cloud shine from particulates are also presented in Figure 15. As noted earlier, the health effects associated with ground deposition are calculated with a more realistic dose assessment model than was used in the RSS. This category accounted for most of the latent health effects in that study, due in part to the high release percentages assumed and in part to the conservative dosimetric model. However, the RSS considered evacuation is not included in the present analysis.

The number of potential cases of latent thyroid cancer resulting from inhalation of radioiodines, associated with a 1 percent radioiodine inventory release, are reported in Figure 16.

Table 4 presents a comparison of the conservatively calculated potential health effects at the selected specific site for a 24 hour release of radioactive material starting 2½ hours after shutdown of the reactor. The health effects are compared for two source terms: the RSS PWR Release Category 2 source term and the SWEC proposed interim source term of 100 percent noble gases and 1 percent radioiodines and 1 percent particulates. The results are for an actual site and are not taken directly from the RSS, which used a hypothetical site based on data from several sites.

The number of calculated early and latent fatalities reported in Table 4 from noble gases, radioiodines, and particulates are not additive, as many individuals in the population are exposed to all three categories of doses resulting in different combined health effects.

In addition to the dramatic decrease in the number of calculated health effects associated with the SWEC recommended interim source terms, it should also be pointed out that the latent health effects are statistical effects, related to population man rem analyses in combination with linear dose response hypotheses.

As noted earlier, Stone & Webster Engineering Corporation invites your comments on this paper in order to help guide its future efforts in pursuing the important source term question in conjunction with others in the nuclear safety analysis community.

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TABLE 1

COMPARISON OF SOURCE TERMS

	Percentage of Core Inventory Released to the Containment*						
	Xe-Kr	I	Cs-Rb	Te-Sb	Ba-Sr	Ru	La
Reactor Safety Study (RSS) Release Category PWR-2	90	70	50	30	6	2	0.4
German Risk Study (DRS)-Phase A Release Category 2	100	39	26	16	3		
German Project for Nuclear Safety (PNS)Release Category 2	100	0.64	0.69	0.56	0.69		
TID-14844	100	25	1	1	1	1	1
SWEC Proposed Interim Source Term	100	1	1	1	1	1	0.4*

*The released airborne radioactivity in the containment atmosphere is subsequently released directly to the environment in the RSS. The DRS and PNS assume other release paths. TID-14844 source term is combined with design basis leak rates from the containment. The SWEC proposed source term is combined with variable time periods for release to the environment and variable release durations.

**The conservative release percentage of 0.4 for the lanthanum group is not proposed to be increased or decreased at this time. Currently available data indicate that this value is extemely conservative.

TABLE 2

MAJOR NATURAL MECHANISMS WHICH AFFECT FISSION PRODUCT RELEASES

NOBLE GASES	• Time delay prior to availability for release
RADIOIODINES	• Time delay prior to availability for release
	• Chemical reactions to form compounds (e.g., CsI)
	• Very little iodine vs other elements (e.g., 7 times as much Cs as I)
	• Thermodynamics (e.g., relative boiling points)
	• Solubility of metal iodides in water
	• Retention in pressure vessel, reactor coolant system, and containment
PARTICULATES	• Time delay prior to availability for release
	• Retention in core material
	• Retention in pressure vessel, reactor coolant system, and containment
	• Thermodynamics
	• Solubility in water
	• Aerosol agglomeration
	• Gravitational settling
	• Condensation
	• Chemical reactions to form compounds

TABLE 3

SMALL BREAK LOCA CHRONOLOGY FOR V SEQUENCE
(Time in Seconds)

EVENT	6 INCH BREAK	4 INCH BREAK	3 INCH BREAK
Break Occurs	0	0	0
Reactor Trip	9	14	22
Top of Core Uncovered	104	268	550
Accumulator Injection Begins (RCS Pressure Reaches 600 Psia)	236	655	1520
Hot Rod Bursts (Location from bottom of core)	241 (10.5 ft)	688 (10.75 ft)	1248 (11.25 ft)
Peak Clad Temperature (Temperature)	260 (1621°F)	676 (1578°F)	1372 (1852°F)
Core Recovered	840	1528	1.4 hr
RWST Emptied-With No Operator Action	1.5 hr	1.5 hr	1.5 hr
RWST Emptied-With Operator Action to Terminate Low Head Safety Injection 30 min. after break occurs	15 hr	15 hr	15 hr

TABLE 4

POTENTIAL HEALTH EFFECTS FOR A 24 HOUR RELEASE STARTING 2½ HOURS AFTER SHUTDOWN

	RSS RELEASE CAT. PWR-2 (90% Noble Gases, 70% Radiodines, 50% Cs-Rb, 30% Te-Sb,6% Ba-Sr, 2% Ru, 0.4% La)	SWEC PROPOSED INTERIM SOURCE TERM (100% Noble Gases, 1% Radiodines, 1% Particulates)
EARLY FATALITIES		
Noble Gases	0	0
Radioiodines	2,500	0
Particulates	11,000	18
LATENT FATALITIES PER YEAR		
Noble Gases	6	8
Radioiodines	208	<1
Particulates	333	17
LATENT THYROID CANCERS PER YEAR		
Radioiodine Inhalation	1,750	25

NOTE: NUMBERS ARE NOT ADDITIVE

CONTAINMENT TEMPERATURE AND PRESSURE AS A FUNCTION OF TIME FOLLOWING A LARGE BREAK LOCA WITH MINIMUM ECCS AND WITHOUT CONTAINMENT SPRAYS

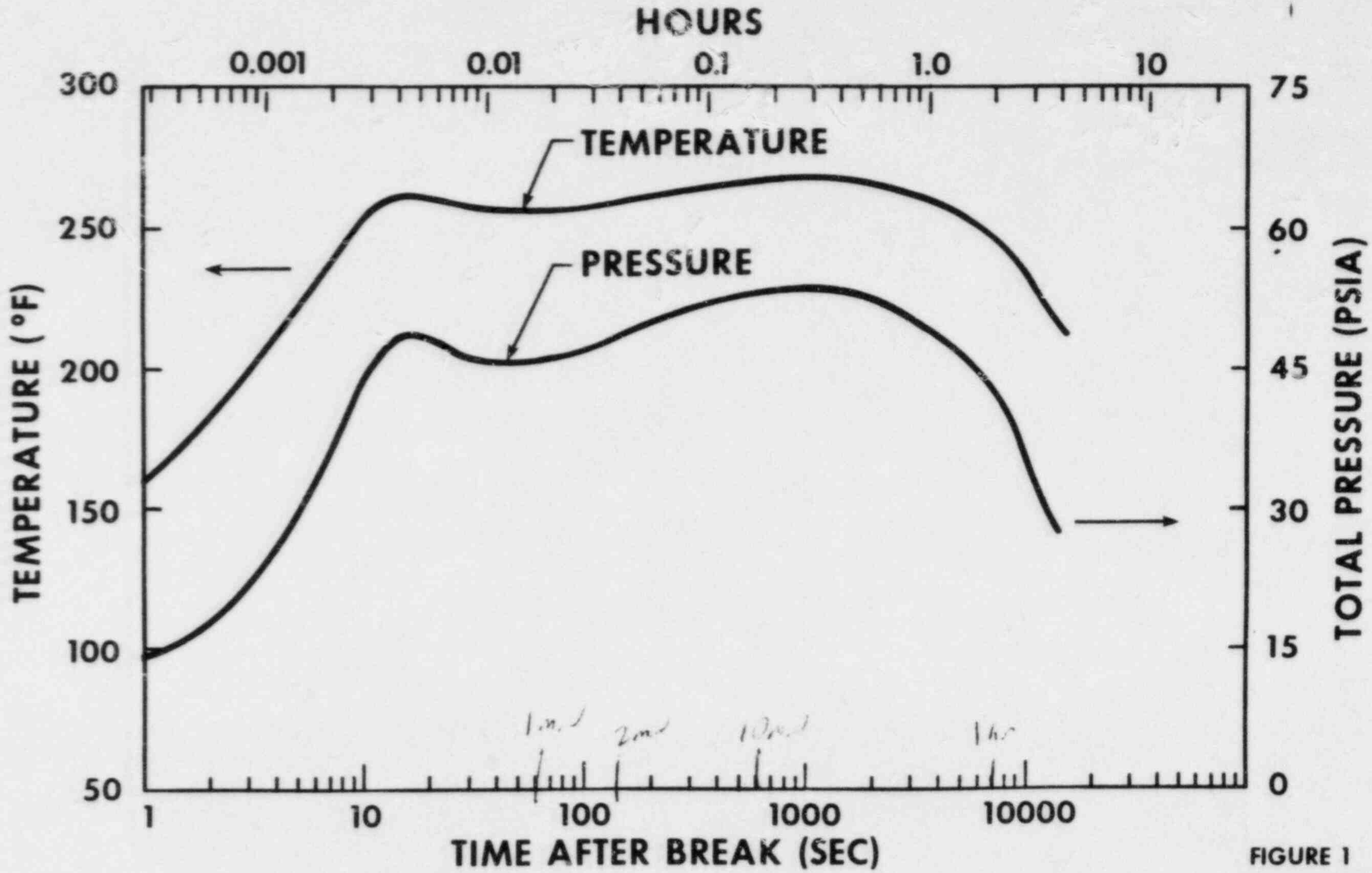


FIGURE 1
STONE & WEBSTER

82-28171

CONTAINMENT STEAM DENSITY AS A FUNCTION OF TIME FOLLOWING LOCA WITH MINIMUM ECCS WITHOUT CONTAINMENT SPRAYS

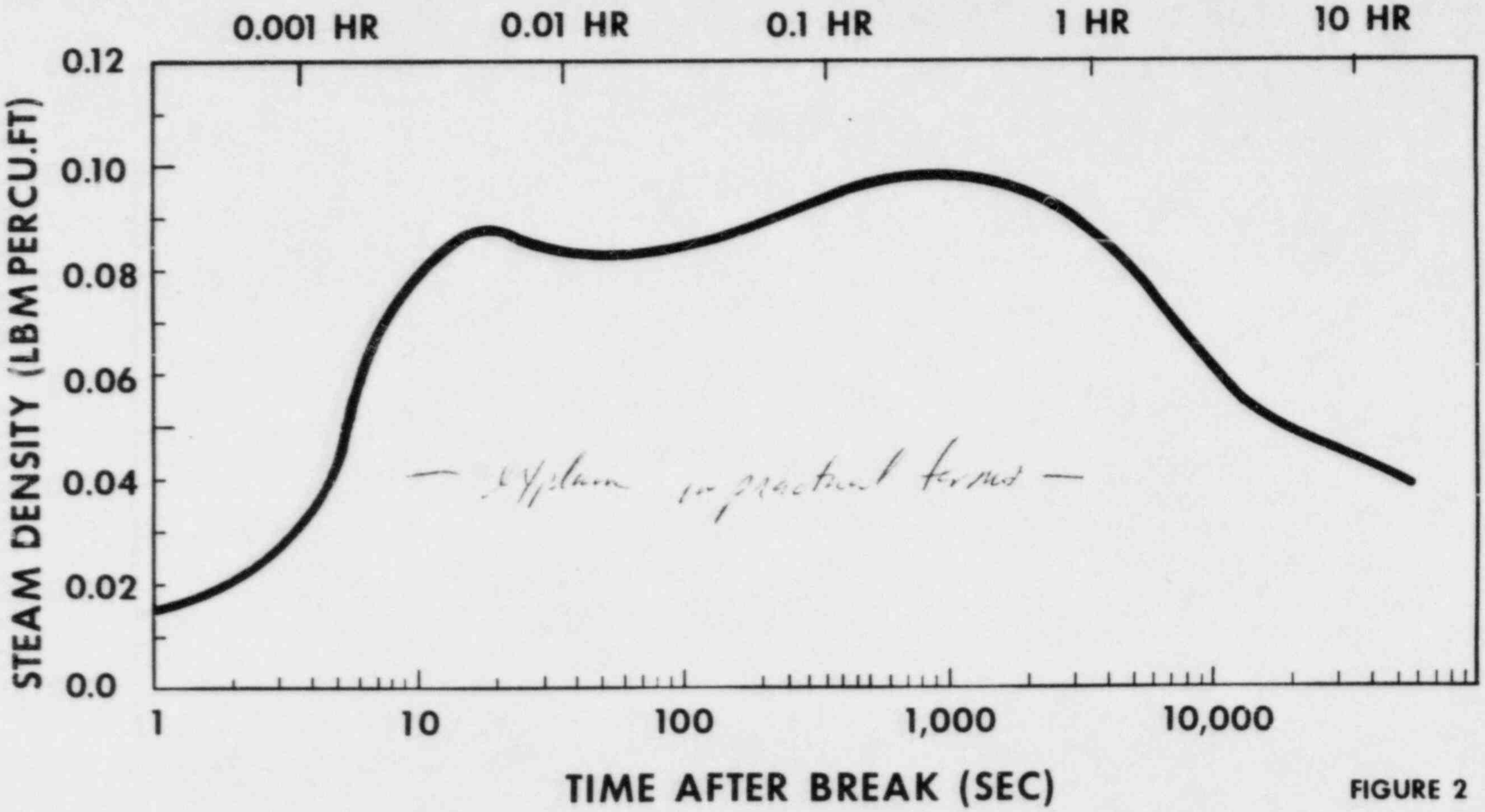
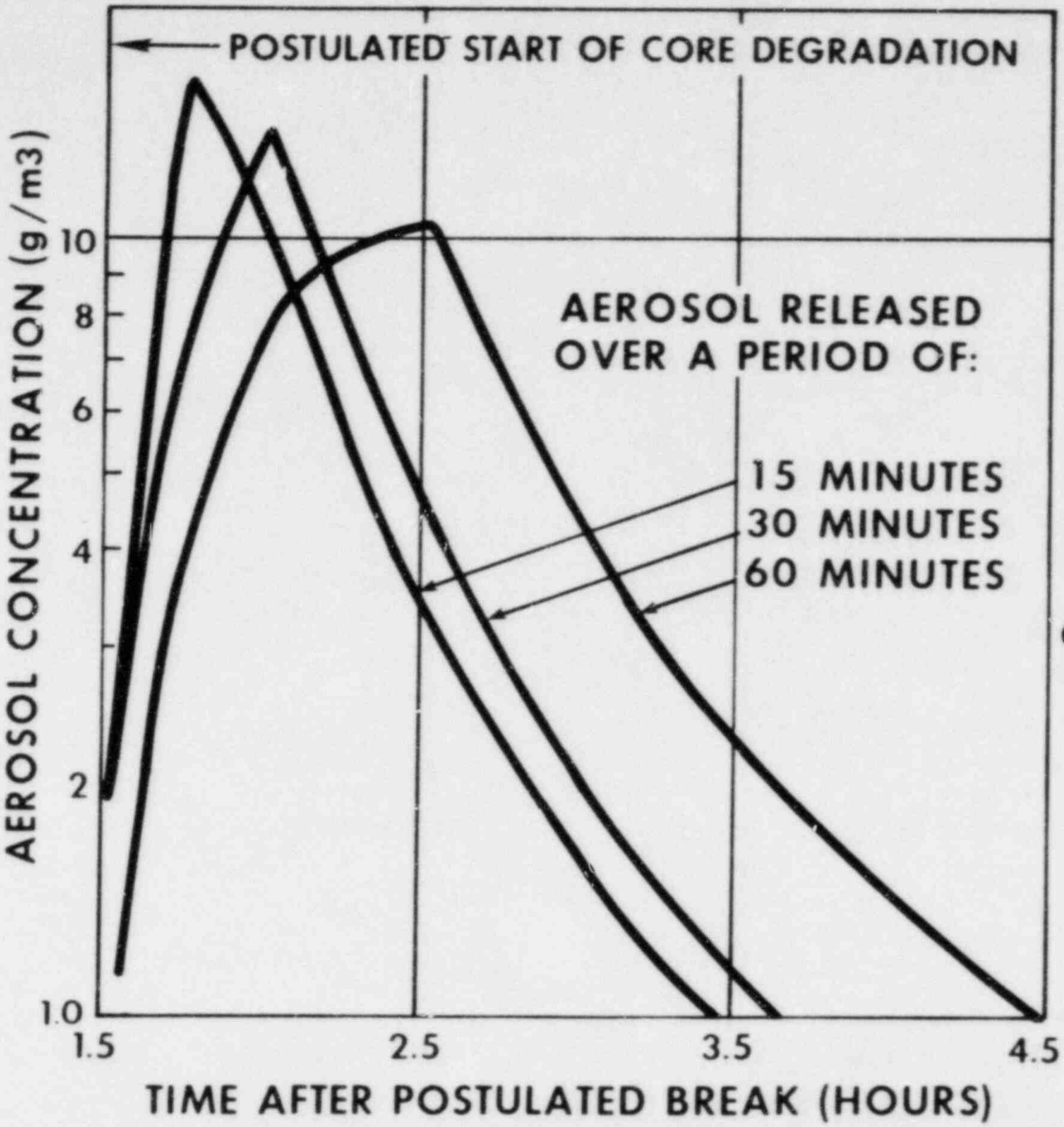


FIGURE 2

STONE & WEBSTER

2-28.172



AIRBORNE AEROSOL CONCENTRATION IN CONTAINMENT ATMOSPHERE

AEROSOL MASS RELEASE - 1,000Kg

CONTAINMENT VOLUME - 54,000m^3 (1.9×10^{6}FT^3)

FIGURE 3

STONE & WEBSTER

12-28,069

TEMPERATURE AND PRESSURE IN 193,000 FT³ VOLUME OUTSIDE CONTAINMENT FOR "V" SEQUENCE

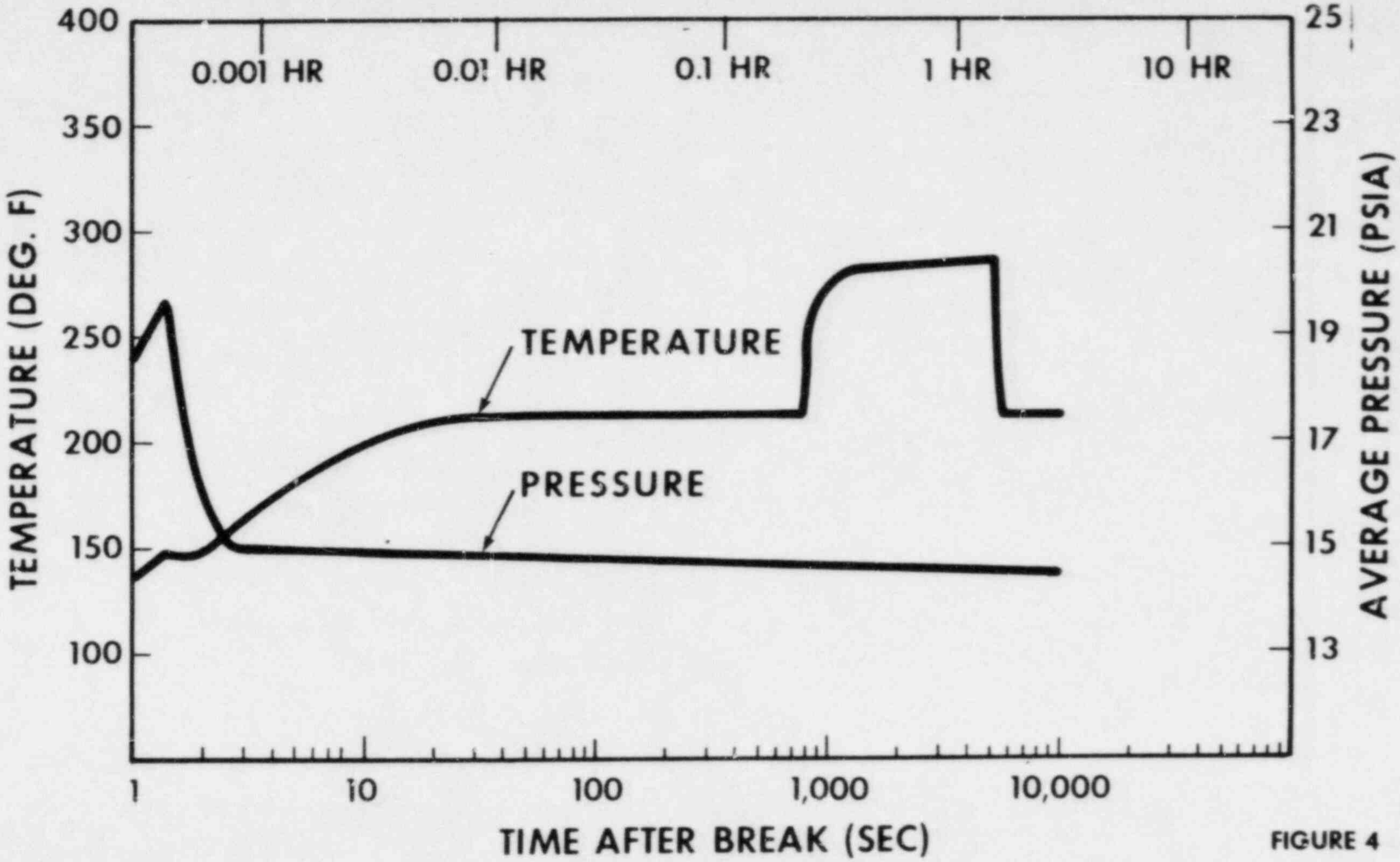


FIGURE 4

STONE & WEBSTER

82-28,068

STEAM DENSITY IN 193,000 FT³ VOLUME OUTSIDE CONTAINMENT FOR "V" SEQUENCE

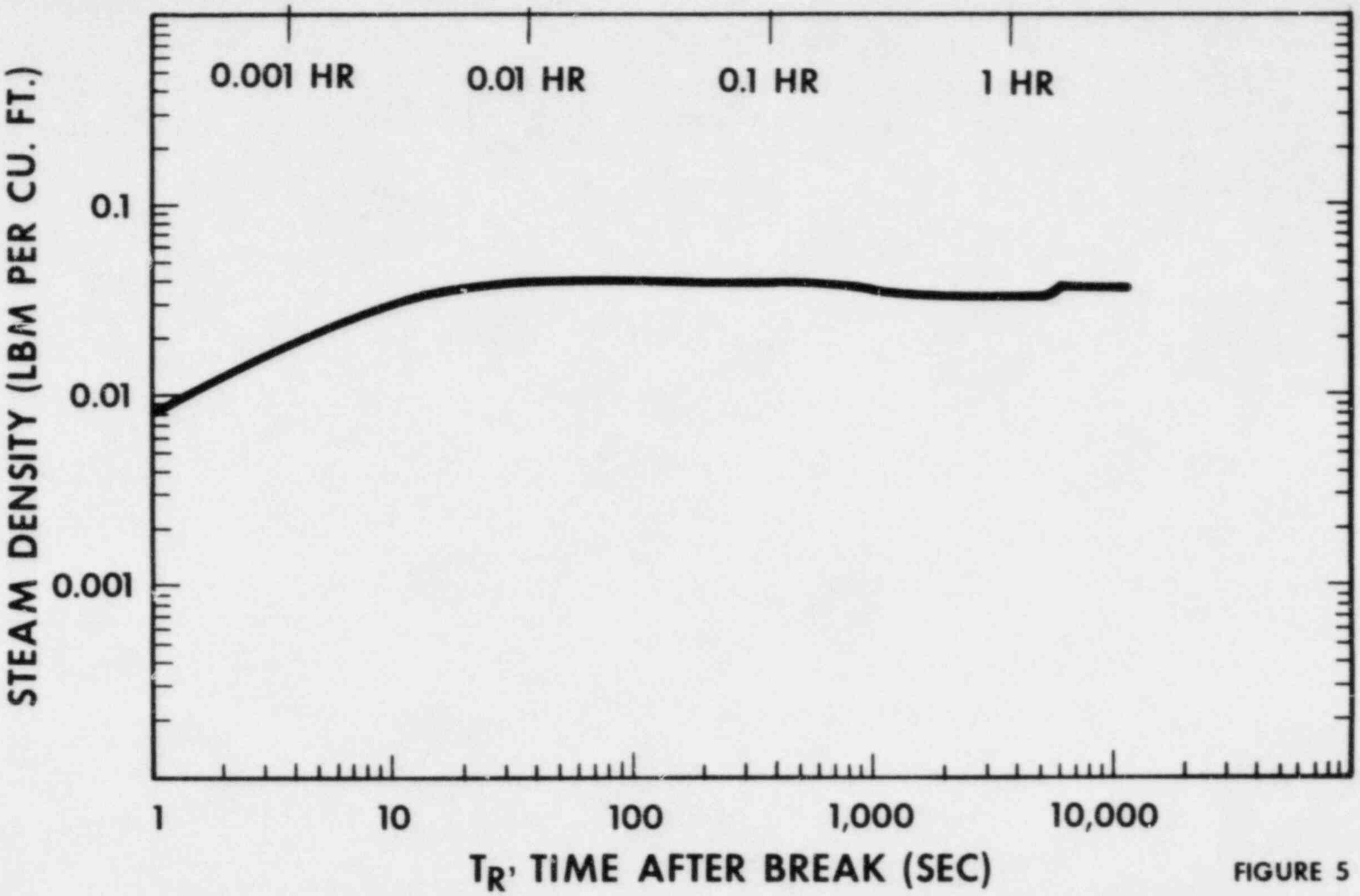
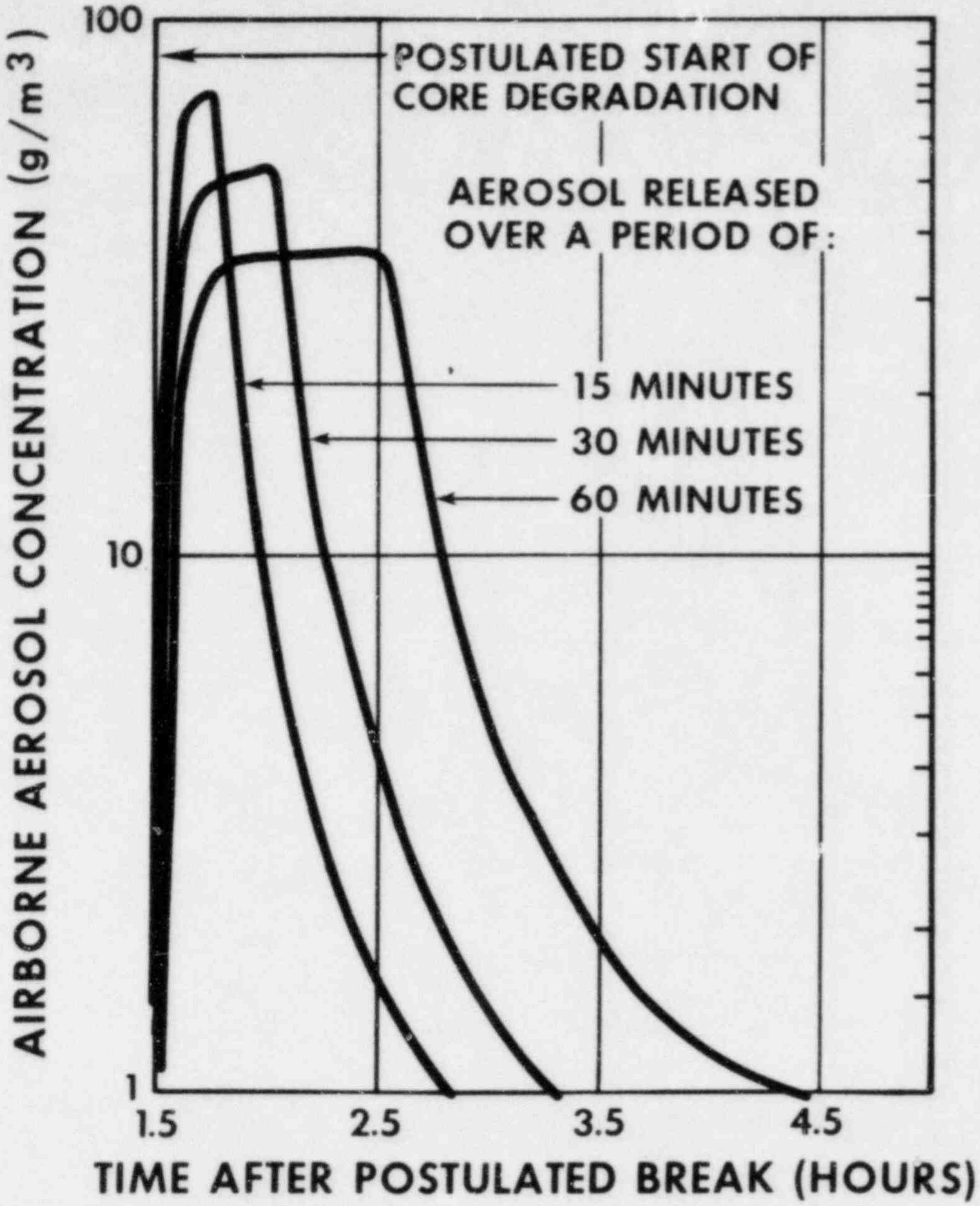


FIGURE 5

STONE & WEBSTER

82-28,067



AIRBORNE AEROSOL CONCENTRATION IN LARGE VOLUME OUTSIDE CONTAINMENT FOR "V" SEQUENCE

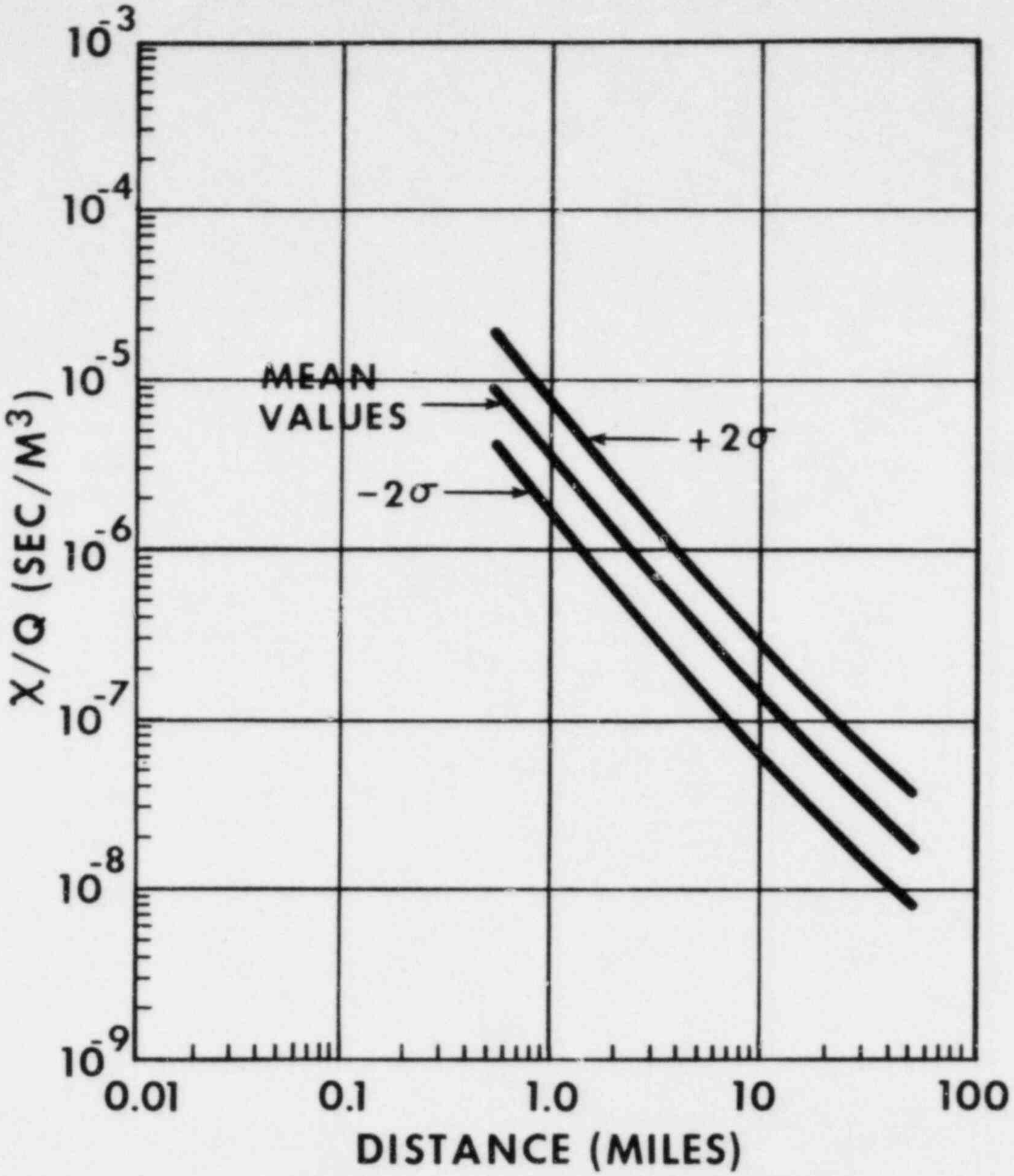
AEROSOL MASS RELEASED = 1000 KG

VOLUME = 5,400 m^3 (1.9×10^5 FT^3)

FIGURE 6

STONE & WEBSTER

2-28,071



ANNUAL AVERAGE χ/Q VALUES FOR EACH OF 42 NUCLEAR SITES

FIGURE 7

WHOLE BODY GAMMA DOSE FROM NOBLE GASES 100% RELEASE OCCURRING AT TIME T_R AFTER SHUTDOWN

(NUREG-0771 CORE INVENTORY)

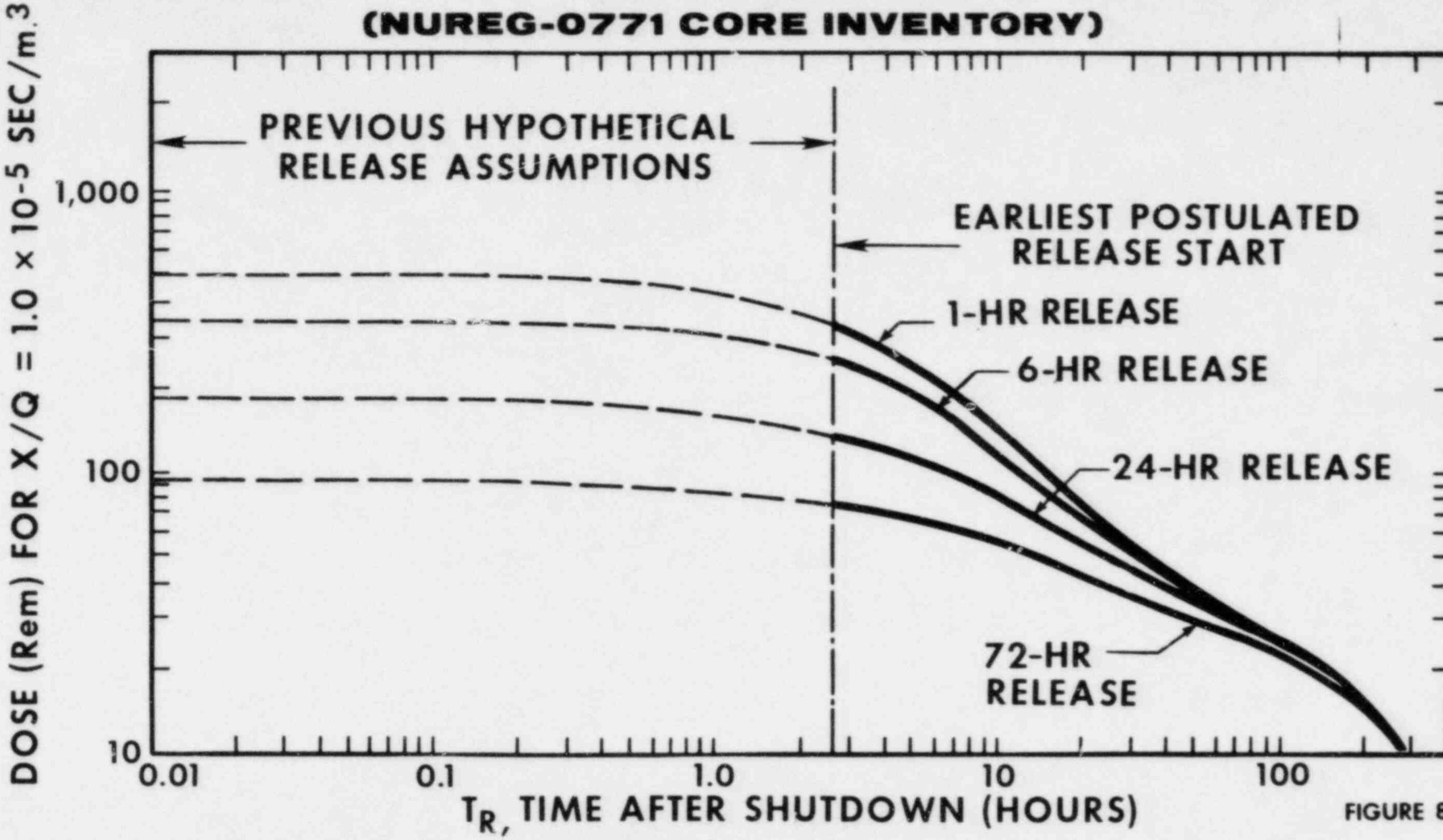


FIGURE 8

STONE & WEBSTER

82-27680

WHOLE BODY GAMMA DOSE FROM 1% RADIOIODINE RELEASE OCCURRING AT TIME T_R AFTER SHUTDOWN
(NUREG-0771 CORE INVENTORY)

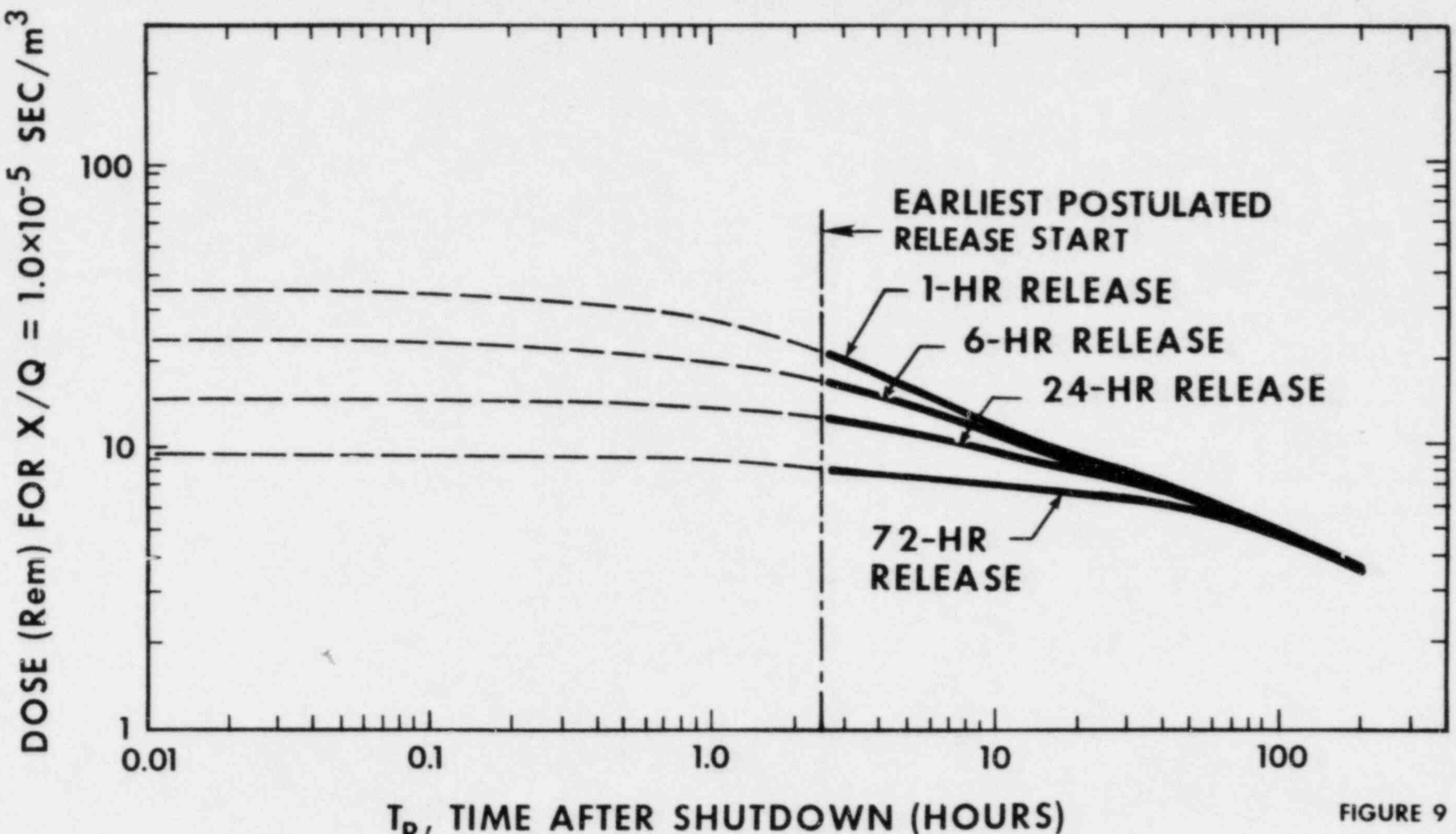


FIGURE 9

STONE & WEBSTER

82-27,679A

WHOLE BODY GAMMA DOSE FROM 1 % PARTICULATES 24-HR RELEASE AFTER 2½ HRS DECAY AS A FUNCTION OF EXPOSURE TIME T_E, TO THE CONTAMINATED GROUND (NUREG-0771 CORE INVENTORY)

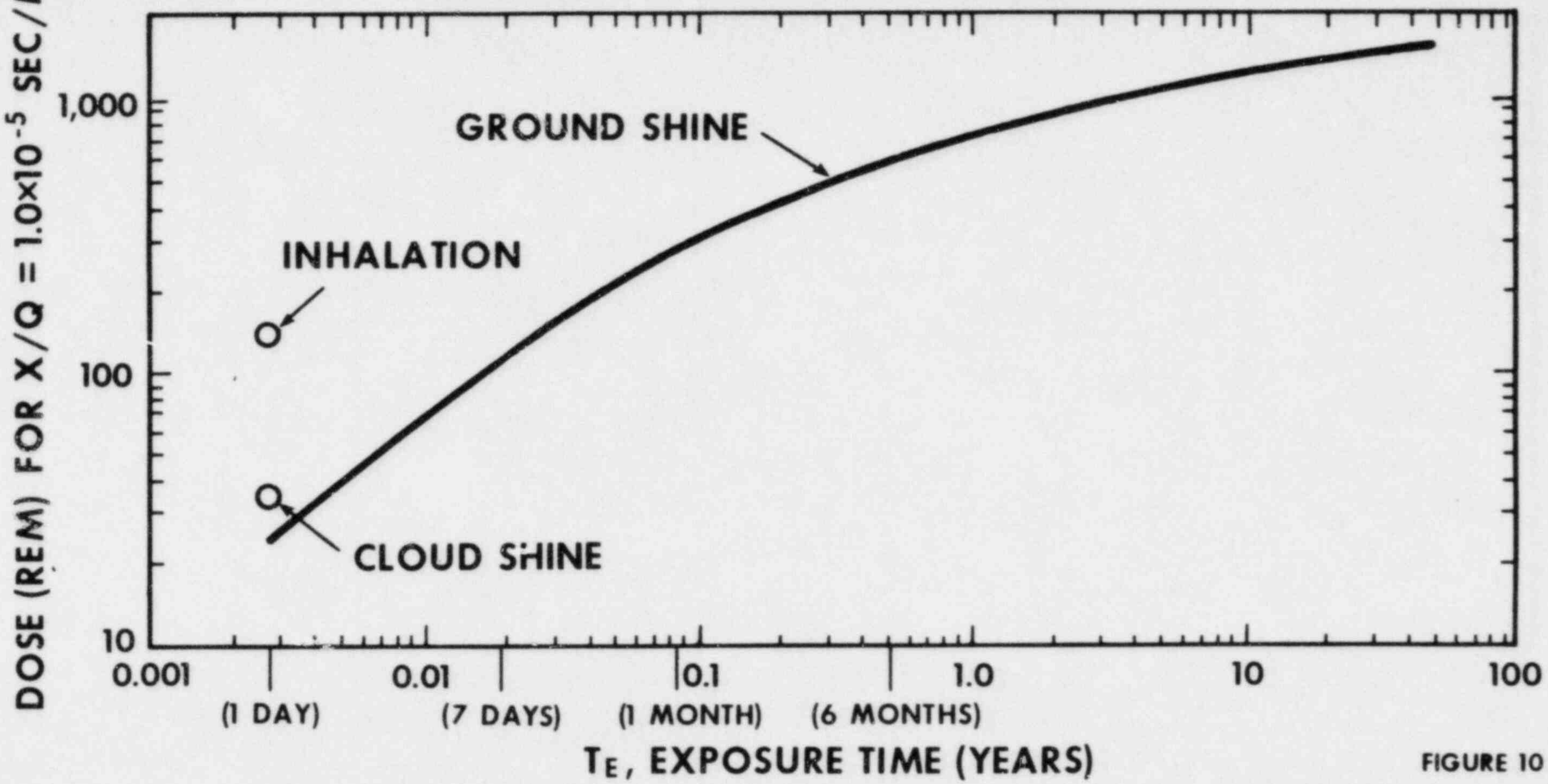


FIGURE 10

STONE & WEBSTER

82-28,089

EARLY FATALITIES AT A SPECIFIC SITE RESULTING FROM 100% NOBLE GAS RELEASE AS A FUNCTION OF TIME AFTER SHUTDOWN

(NUREG-0771 CORE INVENTORY)

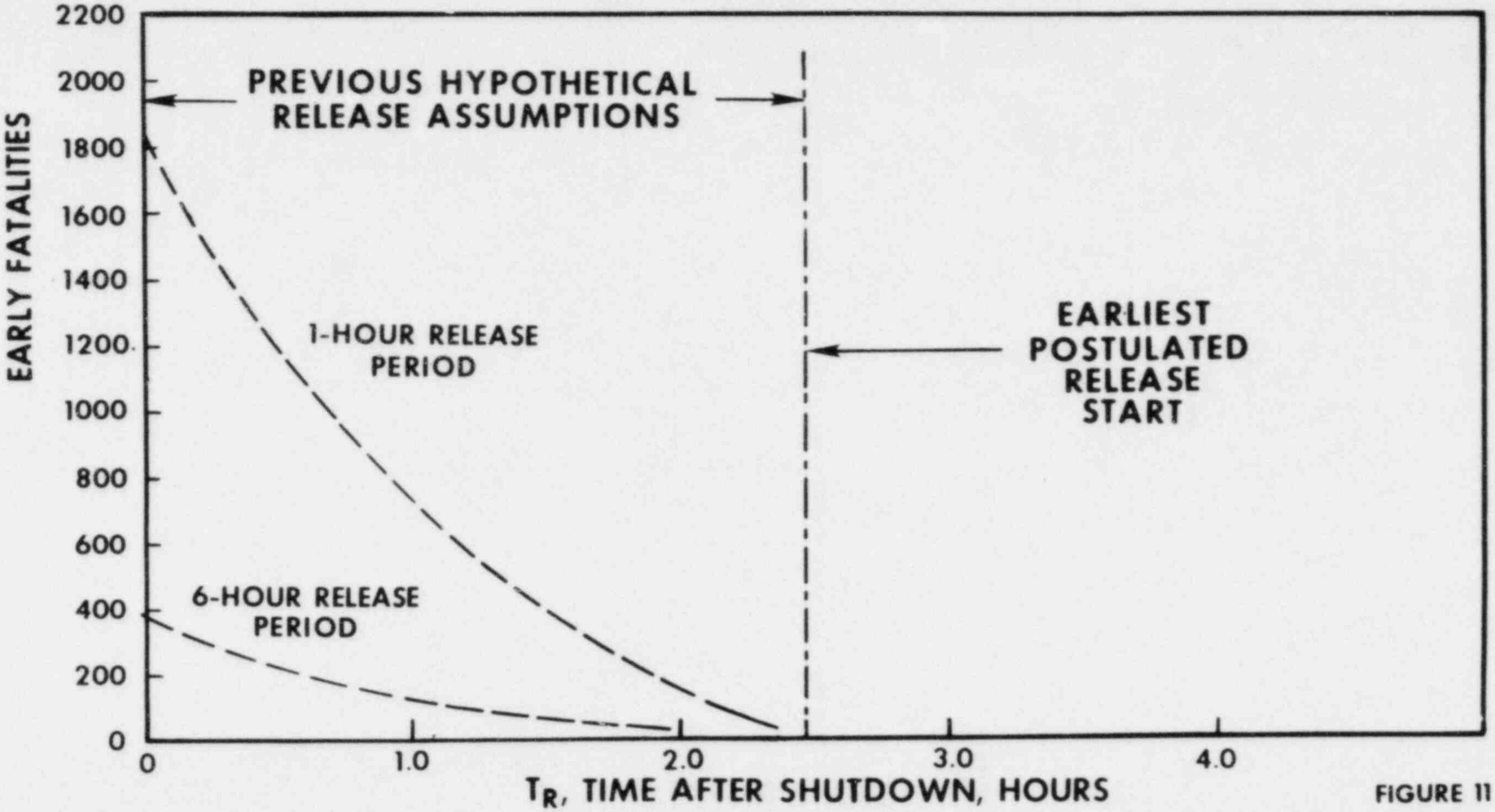


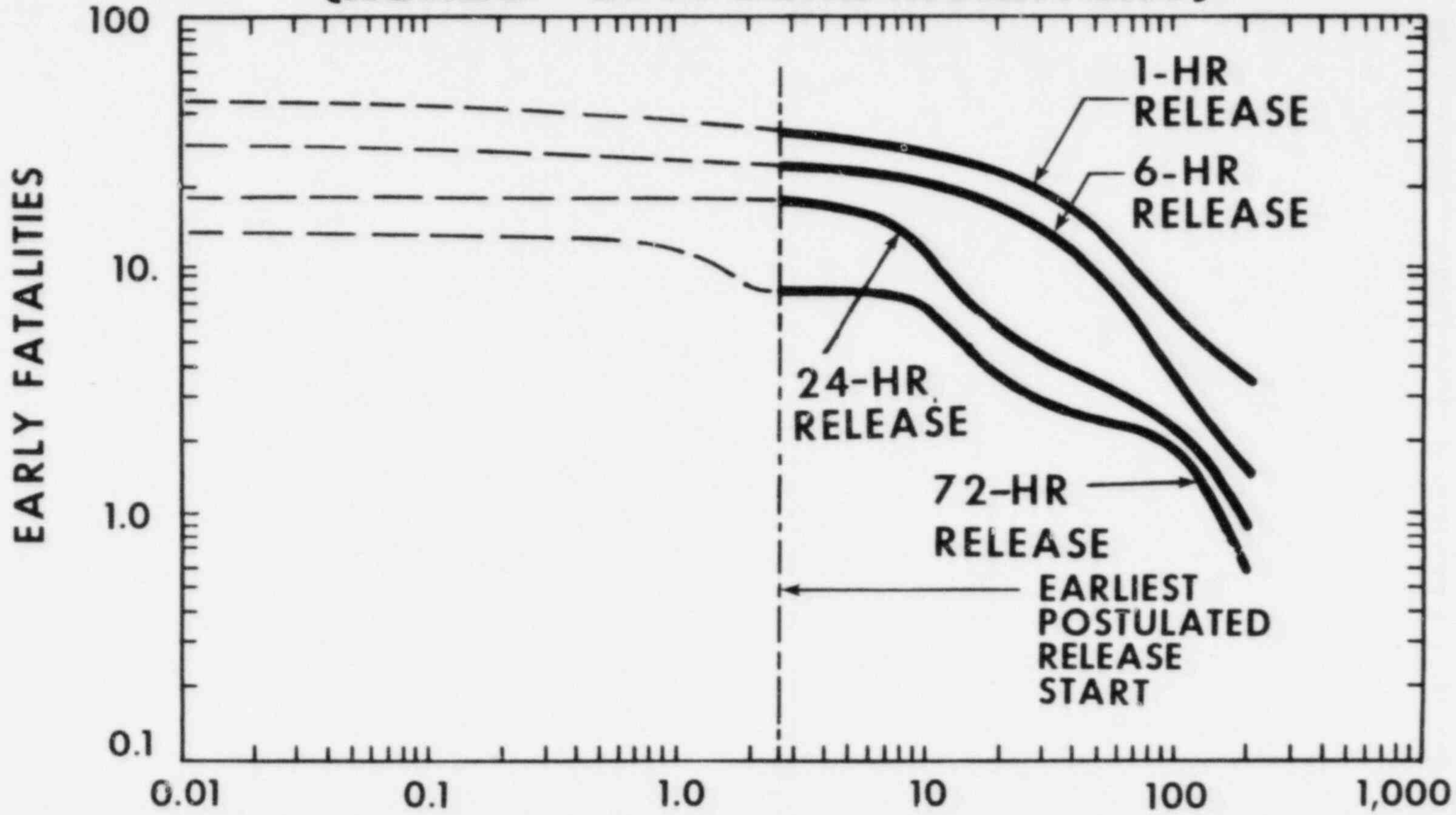
FIGURE 11

STONE & WEBSTER

82-27, 740

EARLY FATALITIES FROM 1% PARTICULATES AT SPECIFIC SITE AS A FUNCTION OF TIME AFTER SHUTDOWN, T_R (FOR 7 DAY EXPOSURE TO GROUND SHINE)

(NUREG - 0771 CORE INVENTORY)



T_R TIME AFTER SHUTDOWN (HOURS)

FIGURE 12

STONE & WEBSTER

2-28, 1773

LATENT FATALITIES AT A SPECIFIC SITE RESULTING FROM 100% NOBLE GAS RELEASE AS A FUNCTION OF TIME AFTER SHUTDOWN

(NUREG - 0771 CORE INVENTORY)

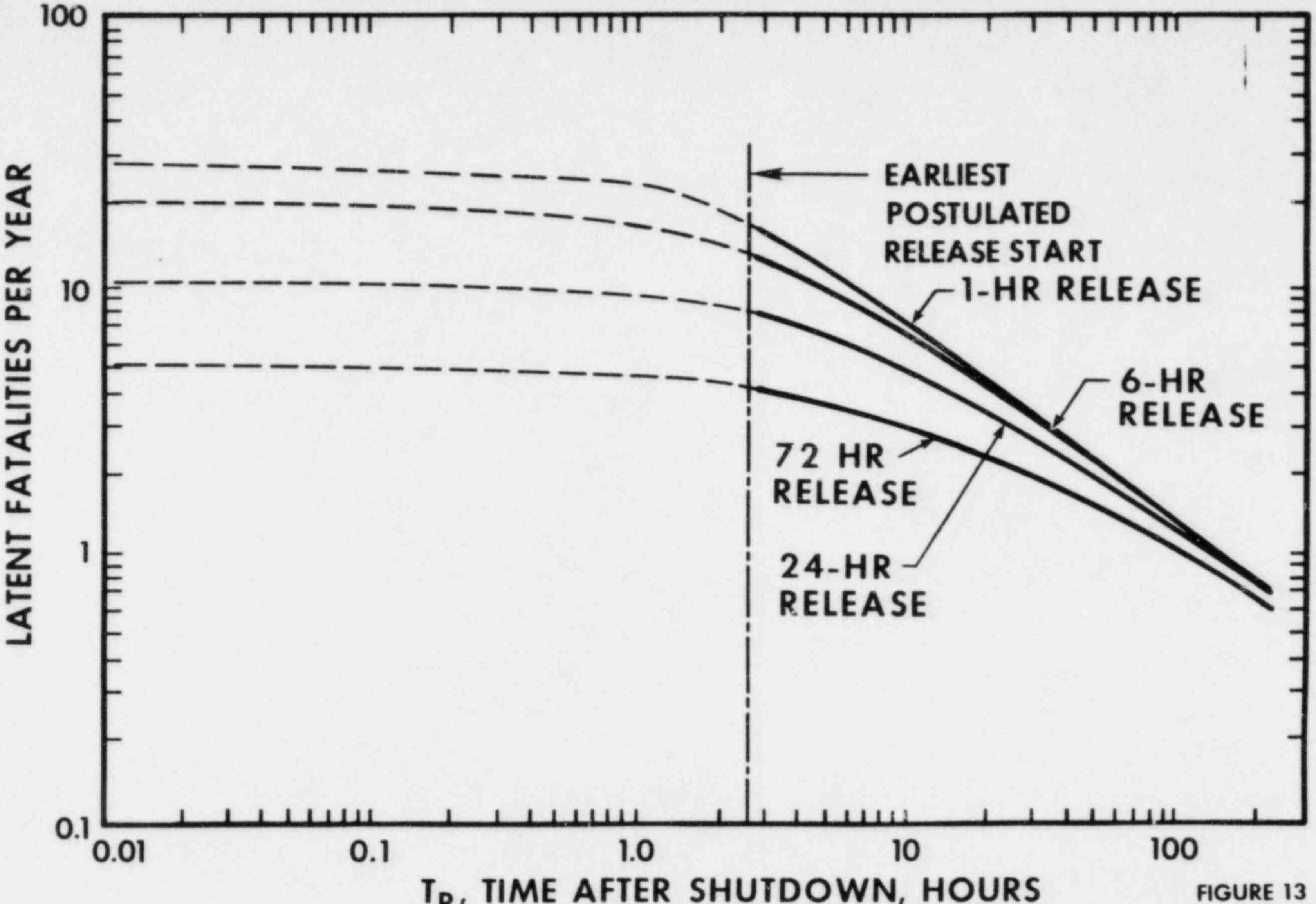
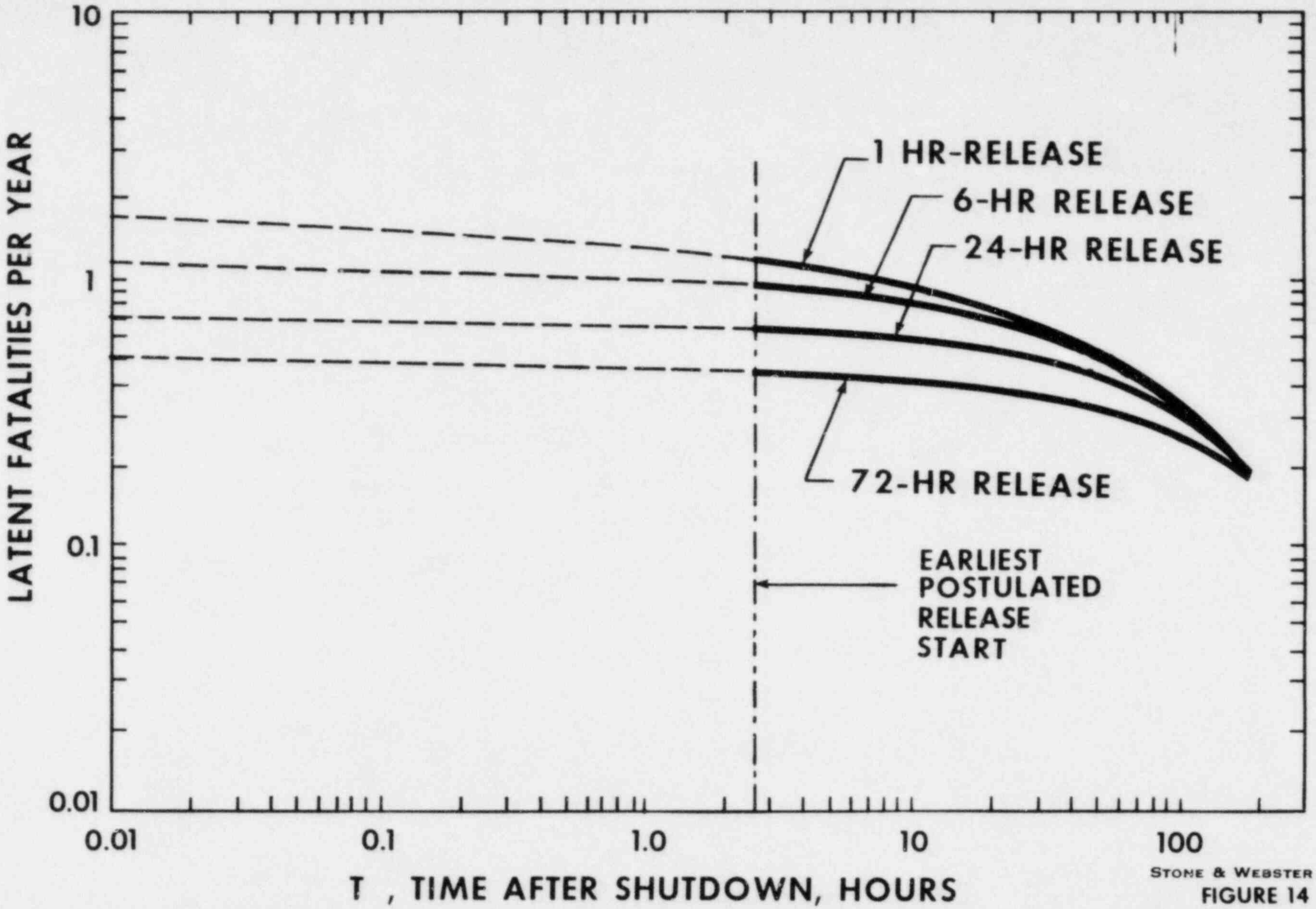


FIGURE 13

STONE & WEBSTER

LATENT FATALITIES AT A SPECIFIC SITE RESULTING FROM 1% RADIOIODINE RELEASE AS A FUNCTION OF TIME AFTER SHUTDOWN

(NUREG - 0771 CORE INVENTORY)



STONE & WEBSTER
FIGURE 14

LATENT FATALITIES AT A SPECIFIC SITE RESULTING FROM 1% PARTICULATES, 24-HR RELEASE AFTER 2½ HRS DECAY, AS A FUNCTION OF EXPOSURE TIME T_E, TO THE CONTAMINATED GROUND

(NUREG-0771 CORE INVENTORY)

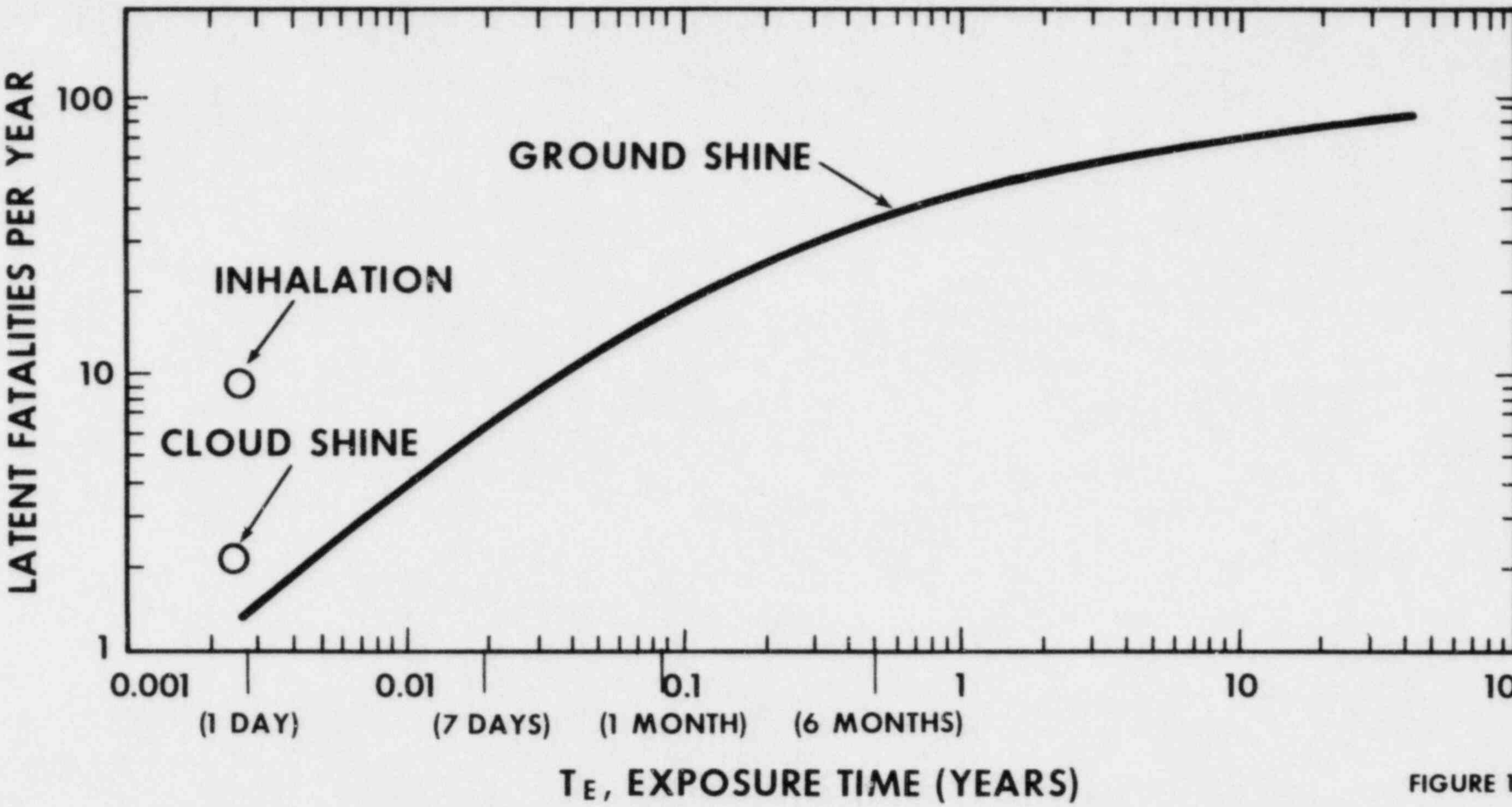


FIGURE 15

STONE & WEBSTER

82-28,090

LATENT THYROID CANCERS AT A SPECIFIC SITE RESULTING FROM 1% RADIOIODINE RELEASE AS A FUNCTION OF TIME AFTER SHUTDOWN

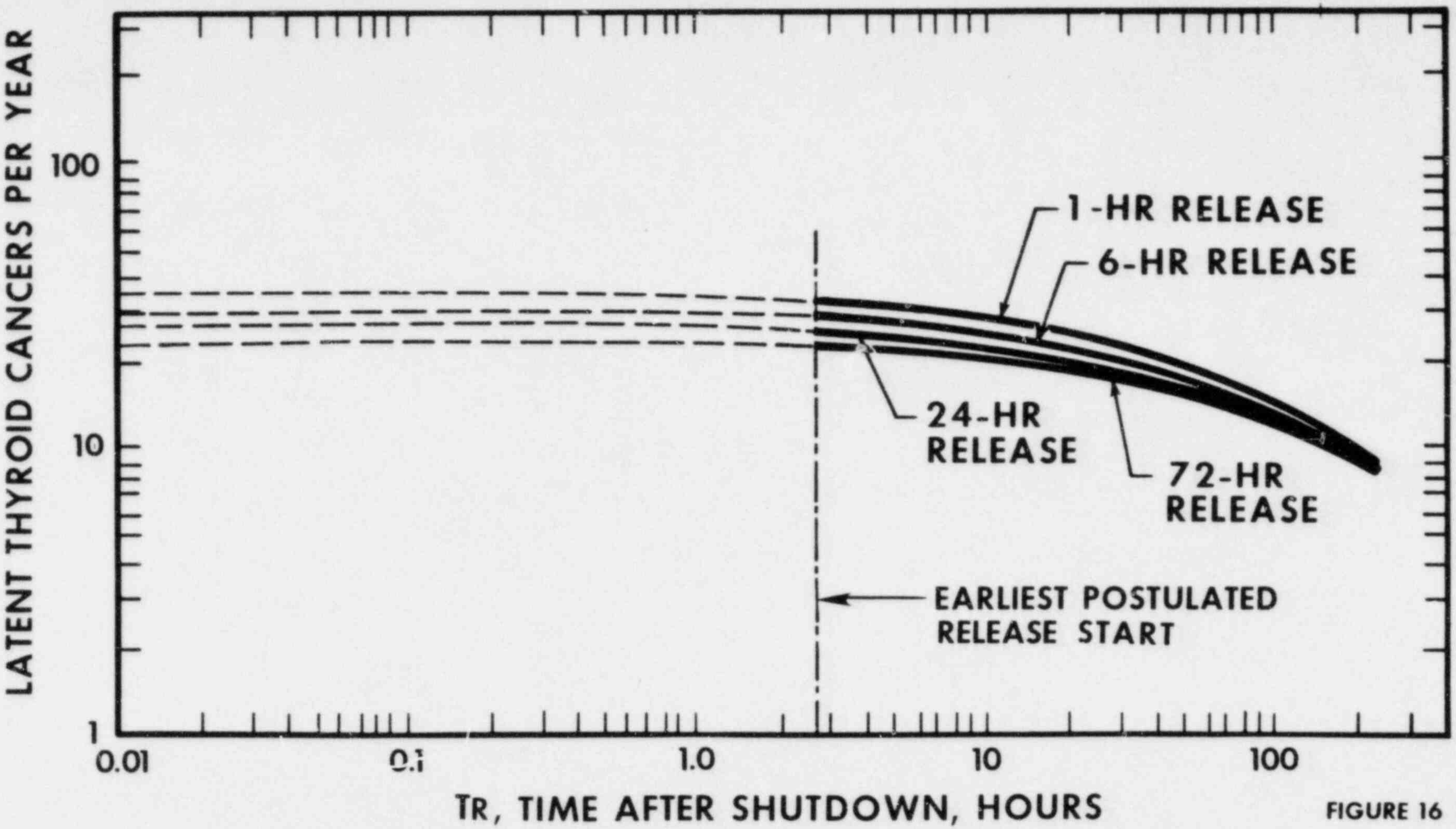


FIGURE 16

STONE & WEBSTER

82-27,744

"ASSESSMENT OF THE RADIOLOGICAL CONSEQUENCES OF POSTULATED REACTOR ACCIDENTS"

Summary of a Paper by
E.G. Warman, Chief Engineer, Nuclear Technology Division,
Stone & Webster Engineering Corporation, Boston, Massachusetts
Presented at the Second International Conference on Nuclear Technology Transfer
Buenos Aires, Argentina, November 2, 1982

When nuclear power was in its infancy, Federal regulators established extremely conservative assumptions as to the release of radioactive material to the environment in the event of a catastrophic accident, one involving a core meltdown. That approach was appropriate at the time because of the lack of firm data on which certain benchmarks, such as the "source term," could be based. The source term defines the timing, amount and type of release of radioactive material from the confines of a nuclear power plant.

These early, ultra-conservative assumptions of the old Atomic Energy Commission continue to be used today, although a vast amount of new data has become available in recent years which clearly demonstrates that such ultra-conservatism is counter-productive. The new data result from the considerable research on nuclear-power-plant safety recently performed in the United States and Germany, and from actual experience in the Three Mile Island accident in 1979.

Continued use of these outmoded assumptions has had several bad effects, including unrealistic time and distance conditions for evacuation and unnecessary requirements for the distribution of potassium iodide pills, which in turn have generated unwarranted public fears. Furthermore, there obviously are economic penalties associated with such superfluous safety measures.

Early in 1981, Stone & Webster Engineering Corporation, with the assistance of prominent outside experts, began a concentrated reassessment of the source-term issue. The reassessment now is sufficiently complete to be reported in detail, which is the purpose of this paper. The results of the reassessment have been given to the Nuclear Regulatory Commission.

The conclusions of the SWEC study with respect to each of those three basic components of the source term are:

(1) The release of radioactive iodine has heretofore been considered the greatest threat to public health. The long-standing assumption has been that 50 percent of the iodine in the core and primary coolant system would escape, and that half of this escaped iodine would remain airborne in the containment. Experience and analysis by nuclear-safety experts, including those at Stone & Webster, have shown that no more than one percent of the total radioiodine would be available for release from the containment in the event of a core meltdown. The rest would react with various substances to form metal iodides, which are extremely soluble in water, and thus would be held in the containment.

(2) Noble gases have always been considered to pose only a slight public health threat in the event of a severe accident. The existing source term assumes that about 90 percent of the available noble gases would escape the containment during and immediately after a severe accident. Stone & Webster's study confirms this estimate and, in fact, suggests that 100 percent of the gases might escape.

F/4

(3) Particulate fission products could pose a long-term contamination threat to water and soil, but would represent insignificant direct radiation to individuals. Previously it has been assumed that up to 50 percent of the radioactive particulates in the core and primary coolant system would be available for release to the environment. Stone & Webster's assessment shows that an estimate of one percent is more realistic although still highly conservative. Particulates would be released from a severely damaged core in the form of dense aerosols which would agglomerate with other material and settle within the containment.

Following its reassessment, SWEC used the new figures--replacing the source term figures in the NRC Reactor Safety Study (RSS)--to calculate consequences. This resulted in a tremendous decrease in the number of deaths estimated to occur as a result of a core meltdown in a nuclear power plant. SWEC calculations using the RSS source term, had projected 2,500 deaths from radioiodine and 11,000 from particulates with a population of three million people within 50 miles. However, when SWEC substituted the proposed interim source term for the RSS source term, the results indicated there would be 18 deaths - all from particulates.

As a result of this effort, SWEC proposes that the nuclear community, including the NRC, consider the adoption of an interim source term, pending completion of confirmatory research presently in progress.

The proposed interim source term compares with that used in the NRC's Reactor Safety Study as follows:

Radioactive Material Group	NRC Reactor Safety Study	SWEC Proposed Interim Source Term
Noble Gases	90%	100%
Radioiodides	70%	1%
Cesium-Rubidium	50%	1%
Tellurium-Antimony	30%	1%
Barium-Strontium	6%	1%
Ruthenium	2%	1%
Lanthanum	0.4%	0.4%

Stone & Webster has analyzed the potential health effects of a hypothetical severe nuclear-power-plant accident at a typical site using both the NRC Reactor Study source term and the proposed interim source term.

The results are summarized below:

STONE & WEBSTER CALCULATED
POTENTIAL HEALTH EFFECTS FOR A 24-HOUR RELEASE
STARTING 2-1/2 HOURS AFTER SHUTDOWN*

	NRC Reactor Safety Study Source Term	SWEC Proposed Interim Source Term
Early Fatalities		
Noble Gases	0	0
Radioiodides	2,500	0
Particulates	11,000	18
Latent Fatalities Per Year		
Noble Gases	6	8
Radioiodides	208	1
Particulates**	333	17
Latent Thyroid Cancers Per Year		
Radioiodide Inhalation	1,750	25

*Note: Numbers are not directly additive
**Based on exposure to contaminated ground for seven days