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MEMORANDUM FOR: D. Ross, Deputy Director
Division of Project Management

FROM: T. P. Speis, Chief
Advanced Reactors Branch, DPM

SUBJECT: REVISED REPORT ON DEGRADATION TO CORE MELT IN TMI-2

Enclosed is a revised report prepared by the Advanced Reactors Branch staff (Marchese, Long, Carter, Speis) on core meltdown evaluations for the Three Mile Island (TMI-2) nuclear power plant. This revised report should supersede the rough draft report transmitted to you on April 13, 1979. Compared to the earlier version, this revised version provides additional discussion and calculations, especially in the areas of hydrogen generation and steam explosion phenomena.

Please contact us if we can be of further assistance.

Themis P. Speis, Chief
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Enclosure:
Revised Report - TMI-2

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XIII. Degradation to Core Melt

For contingency planning purposes in dealing with the accident at the Three Mile Island (TMI) nuclear power plant, the NRC staff and its consultants have performed core meltdown analyses in the highly unlikely event of a loss of both natural convection cooling and ECCS injection. These evaluations considered the transient response of the reactor vessel and containment building to phenomena associated with (a) core melt penetration, (b) hydrogen generation and potential for explosion, and (c) potential for steam explosions. Each of these areas is discussed in separate sections below.

Analyses were performed assuming core melt occurs fourteen (14) days (April 11. 1979) and twenty-one (21) days (April 18, 1979) following the initiating accident event at TMI. Actual plant conditions, including the operating decay heat history, were used for these calculations. It should be noted that the core melt consequences would improve slowly as more time passes from the start of the initiating accident on March 28, 1979 to the point at which core meltdown begins. The response of the containment building to a core meltdown was evaluated for different scenarios involving the functioning or non-functioning of the containment cooling system and the containment spray system. These systems will not significantly affect the progression of a core melt front advance but are important in mitigating the associated containment response and radioactivity releases.

XIII.a. Core Melt Penetration

As part of extensions of WASH-1400 evaluations, the NRC is sponsoring work at the Battelle Columbus Laboratories (BCL) to develop analytical tools for analyzing LWR core meltdown accident phenomena. BCL is in the process of developing an LWR meltdown accident analysis computer program called the "MARCH" code. This code includes modeling routines of meltdown thermal-hydraulics and containment response. The meltdown thermal-hydraulics part includes modeling subroutines for calculating the primary system transient, core meltdown sequence, reactor vessel melt-through, core debris fragmentation, and core debris - concrete interactions. The containment response includes modeling subroutines for calculating the containment temperature and pressure history of a meltdown accident, the intercompartment flows, the compartment atmosphere composition, and the time dependent leakage.

Although the MARCH code is in the preliminary stages of development and there are uncertainties in certain areas, the code represents the best analytical tool available for performing LWR core melt accident evaluations and is the tool that the NRC staff and its consultants at BCL relied on for the TMI core melt evaluations. In addition, the NRC staff has performed selective hand calculations in certain areas of the core melt sequence as a check against the computer code predictions. The computer code and hand calculations were found to be in reasonable agreement.

Assuming all coolant flow to the core stops at 21 days (April 18, 1979) following reactor trip at TMI, the base case or the most likely core melt accident sequence of events with containment coolers and sprays functioning (they have been working successfully) is as follows:

TIME = 0	- All coolant flow (either natural convection or ECCS injection) to the core stops at 21 days after reactor trip.
TIME = 35 hours	- Core is uncovered.
TIME = 39 hours	- Core begins to melt.
TIME = 45 hours[1]	- Lower reactor vessel head fails due to the combined thermal and mechanical loads.
	- Core melt falls into pool of water on floor of reactor cavity.
	- Containment pressure goes to about 47 psia due to steam generation.
	- If rapid hydrogen[2] burning occurs, a one-time containment pressure spike of about 75 psia takes place.
	- Core melt starts to penetrate concrete basemat.
TIME = 68 hours	- Core melt penetrates about 18 in. into concrete.
	- Containment pressure increases to about 78 psia.[3]
TIME = 3 to 14 days	- Core melt penetrates 3 to 6 ft. into concrete basemat and stops.[4]

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[1] Refer to Section XIII.c. for discussion of potential for steam explosion either inside of reactor vessel or inside of reactor cavity.

[2] Refer to Section XIII.b. for discussion of hydrogen generation and potential for a hydrogen explosion.

[3] Assumed failure point for containment is 135 psia which is about twice the design pressure.

[4] Because the fuel decay heating is so low at this point in time, our best technical judgment is that the core melt debris would not penetrate the 13 ft. containment basemat. In addition, dissolution and mixing of fuel in concrete will further reduce the volumetric heat source and melt temperature resulting in freezing of the core debris within concrete basemat.

Conclusion: - For this base case, the containment building survives.

The results for other core melt scenarios are presented in Table XIII-1. Calculations were performed assuming the functioning and nonfunctioning of containment coolers and sprays. Specifically, the four scenarios considered were: (1) sprays on/coolers on, (2) no spray/coolers on, (3) sprays on/no coolers, and (4) no spray/no coolers. Time intervals of 14 days (April 11, 1979) and 21 days (April 18, 1979) following reactor trip were also considered.

Referring to the results presented in Table XIII-1, some important conclusions that can be drawn from these calculations are as follows:

1. If containment coolers are functioning, the containment will remain intact following a core meltdown event. Without containment coolers working, containment will fail at about 12 to 14 days due to overpressurization resulting primarily from steam generation.
2. Because decay heating is so low at this point and changing so slowly, the core melt sequence does not improve significantly in comparing the 14 to 21 day results.
3. For either the containment coolers working or not working, the containment sprays do not have a significant effect on the core melt time sequence and containment pressures.

4. The core melt debris will not penetrate the entire 13 ft. containment basemat because decay heating is so low and dissolution and mixing of fuel in concrete will result in freezing of the molten core within the concrete basemat.
5. As discussed in Sections XIII.b. and XIII.c., steam explosions and hydrogen explosions may occur but are not expected to rupture containment. If containment is ruptured by a steam or hydrogen explosion, failure would occur at a minimum of 36 hours and 45 hours (following loss of all coolant flow to core) for the 14 day and 21 day sequences, respectively.

TABLE XIII - 1

RESULTS FOR CORE MELT TIME SEQUENCE AND ASSOCIATED CONTAINMENT PRESSURES

	Sprays[4] On/Coolers On[5]		No Spray/Coolers On		Spray On/No Coolers		No Spray/No Coolers	
Core Flow Stops[1] (Time=0)	14 days	21 days	14 days	21 days	14 days	21 days	14 days	21 days
Core Uncovers	28 hrs 15 psia[2]	35 hrs 15 psia	28 hrs 15 psia	35 hrs 15 psia	28 hrs 21 psia	35 hrs 21 psia	28 hrs 31 psia	35 hrs 29 psia
Core Melt Begins	31 hrs 15 psia	39 hrs 15 psia	31 hrs 15 psia	39 hrs 15 psia	31 hrs 20 psia	30 hrs 20 psia	31 hrs 29 psia	39 hrs 27 psia
Lower RV Head Fails	36 hrs (30-76 psia)[3]	45 hrs (29-41 psia)	36 hrs (30-71 psia)	45 hrs (30-71 psia)	36 hrs (38-73 psia)	45 hrs (42-83 psia)	36 hrs (46-73 psia)	45 hrs (44-73 psia)
Melt Interacts with RC Water	36 hrs (49-72 psia)	45 hrs (47-75 psia)	36 hrs (49-74 psia)	45 hrs (49-79 psia)	36 hrs (38-68 psia)	45 hrs (42-75 psia)	36 hrs (46-85 psia)	45 hrs (44-85 psia)
Melt Penetration into Concrete Begins	39 hrs (18-75 psia)	48 hrs (18-72 psia)	39 hrs (17-69 psia)	48 hrs (17-69 psia)	39 hrs (28-71 psia)	48 hrs (28-82 psia)	39 hrs (49-71 psia)	48 hrs (46-73 psia)
Core Melt Penetrates 18 in. into Concrete	59 hrs (21-82 psia)	68 hrs (20-78 psia)	59 hrs (20-78 psia)	68 hrs (20-77 psia)	59 hrs (31-74 psia)	68 hrs (31-88 psia)	59 hrs (49-71 psia)	68 hrs (42-79 psia)
Containment Overpressure Failure[6]	None	None	None	None	12 to 14 days	12 to 14 days	12 to 14 days	12 to 14 days

NOTES

1. Initial conditions: primary full of 280°F water at 1000 psia; secondary assumed to be dry.
2. Containment pressure, psia.
3. The first value is the containment pressure due primarily to steam generation; the second value is the one time pressure spike from rapid H_2 burning.
4. Sprays on at 3000 gpm; injection is from RWST and circulation from sump.
5. Three building coolers on.
6. Overpressure failure times were extrapolated. Overpressure failure (at 135 psia) is due to continued steam generation without containment heat removal.

XIII.b. The Potential for Hydrogen Generation and Explosion

The introduction of hydrogen into the containment can create a mixture of gases that are either flammable or explosive. If the mixture is such that the flame front travels at a speed greater than sound, a shock wave is created and the reaction is called an explosion or detonation. Detonations occur in uniform mixtures of hydrogen and air at standard conditions when the hydrogen comprises between 19% and 59% by volume. Flammability occurs over wider limits, usually given as 4% to 75% in air. It is generally considered that normal industrial environments contain sufficient sources of ignition, in the form of sparks or hot spots, to trigger the reaction.

The pressure pulse associated with flames in enclosed spaces can be calculated reasonably well by assuming that the heat of the reaction adiabatically raises the temperature of the reaction products, and then relating this temperature to a pressure peak through the ideal gas law. The value of the heat of reaction to be used depends on whether the reaction product, H_2O, is in gaseous or liquid form. Pressures associated with the shock waves accompanying detonations may be higher than the flame pressures by factors of two to eight, and are geometry dependent.

Figure 1 gives some estimates of flame pressures we have observed in the literature or calculated. The straight line represents pressures from flames of common gases given in the literature.(1) Hydrogen mixtures with air are calculated to yield higher pressures than mixtures of these other gases having the same energy content as shown in the figure. We have calculated other pressures for mixtures including steam under conditions that should bracket the parameters to be expected at TMI, and the initial conditions are given on the figure next to each calculated pressure pulse. The pressure given at each condition, corresponds to the high reaction heat.

The initial conditions of the March 28 pressure pulse were probably about 2 psig, 90°F, 2% steam and 4% hydrogen in the containment. The calculation leads to a maximum of 27-30 psig. compared to the observed value of 28 psig.

In the following discussion, we consider a TMI accident scenario with respect to the possible buildup of hydrogen in containment and its flammability or detonability characteristics.

In the unlikely event that natural convection should fail and the primary system should boil dry at 2500 psi through the pressurizer relief, additional metal-water reactions will occur as the hot core

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(1) P. A. Cubbage and M. R. Marshall, "Pressures Generated in Combustion Chambers by the Ignition of Air-Gas Mixtures" Symposium Series No. 33, Inst. Chem. Eng., London (1972).

becomes exposed. Hydrogen will be formed, primarily from the reaction with the remaining zirconium. Since by this time the entire volume above the core will be dry, some of this hydrogen will be expelled through the pressurizer. Heat balances indicate that the top of the core would be uncovered at 28 hours (35 hrs)* after the failure of natural convection. During the subsequent 8 hr (10 hrs), as the remainder of the core became uncovered, 245,000 cubic feet, stp, of hydrogen would be generated from the remaining estimated 65% of the core zirconium. At 2500 psi, this would displace 13% of the volume of the primary containment. This displacement plus continued steam formation would probably expell from 20 to 50 percent of this hydrogen to containment through the pressurizer, increasing the hydrogen concentration in the containment building atmosphere by 2-5%. Four percent hydrogen in air is sufficient to ignite, causing a pressure spike of 26 psi(1).

As in the earlier bubble sequence, we expect the contribution of radiolytic hydrogen and oxygen to be small, and insufficient to cause an explosion within the vessel.(2)

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*The first time stated is calculated at 14 days after the accident, i.e., April 11. The second time, in parentheses, is for 21 days after the accident, i.e., April 18. The times are calculated by BCL.

(1) P. A. Cubbage and M. R. Marshall, "Pressures Generated in Combustion Chambers by the Ignition of Air - Gas Mixtures" Symposium Series No. 33, Inst. Chem. Eng., London (1972).

(2) Memorandum, R. O. Meyer to R. J. Mattson, "Core Damage Assessment for TMI-2" April 13, 1979.

In the very unlikely event that the drying out of the primary systems goes unnoticed or misinterpreted, as it did before, sampling the containment atmosphere and analysis for hydrogen at this stage will give positive evidence of the metal-water reactions.

At 36 hrs (44 hrs) after the failure of natural convection, the core will be sufficiently melted (about 75%) so that it will drop to the bottom of the vessel. The remaining water may prevent melt-through for several hours, but after this is dry, combined thermal and mechanical damage will certainly proceed rapidly and the core debris will be rapidly expelled to the concrete basemat, driven by the 2500 psi pressure of the primary system. The balance of the hydrogen from the primary system can be considered to be expelled to the containment at this time, bringing the hydrogen concentration up to about 10% if no previous ignition had occurred. This is sufficient to ignite with a pressure pulse of about 35 psi if ignition occurs before any great quantity of steam has filled the containment.

Further hydrogen could be generated by a water reaction with chromium from any stainless steel that had become incorporated with the core debris. The quantity is not expected to exceed 20% of the hydrogen generated from the zirconium and discussed above, however. The thermodynamic relations for other possible hydrogen producing reactions indicate that water will not react with nickel and is very unlikely to react with iron under these circumstances.

Figure 1 shows the flame pressures calculated for mixtures with various quantities of steam augmenting the pressure in the containment building. Mixtures up to 50% steam at elevated pressure and temperature conditions appear to define a band of pressure pulses lying between 30 and 50 psi higher than the pressures generated by the common hydrocarbon gases at the same energy content. If we conclude from the accident scenarios that the maximum amount of hydrogen to be released is between about 8 and 12% of the containment volume, a region of the maximum anticipated pressure pulses can be visualized as shown on Figure 1. These pressures are between 45 and 80 psig. This is not out of line with our understanding of the BCL calculations described in Section XIII.a.

All the above calculations (including BCL) have been made without allowance for detonation, as the mixtures, if assumed to be uniform throughout containment, are below the explosive limit. Nonuniform pockets of higher concentration may lead to limited detonations, with somewhat unpredictable but generally higher pressures, due to the propagation and reflection of shock waves.

We recommend that as a precautionary measure, sampling of the containment atmosphere for hydrogen be continued while the core is in a natural convection mode, with special emphasis at any time there may appear to be sustained interruptions in the circulation. We also note that, with pumps off, the early stages of formation of a hydrogen bubble in the vessel may not be apparent except through a careful material balance. In the long-term, radiolytic hydrogen should be considered.

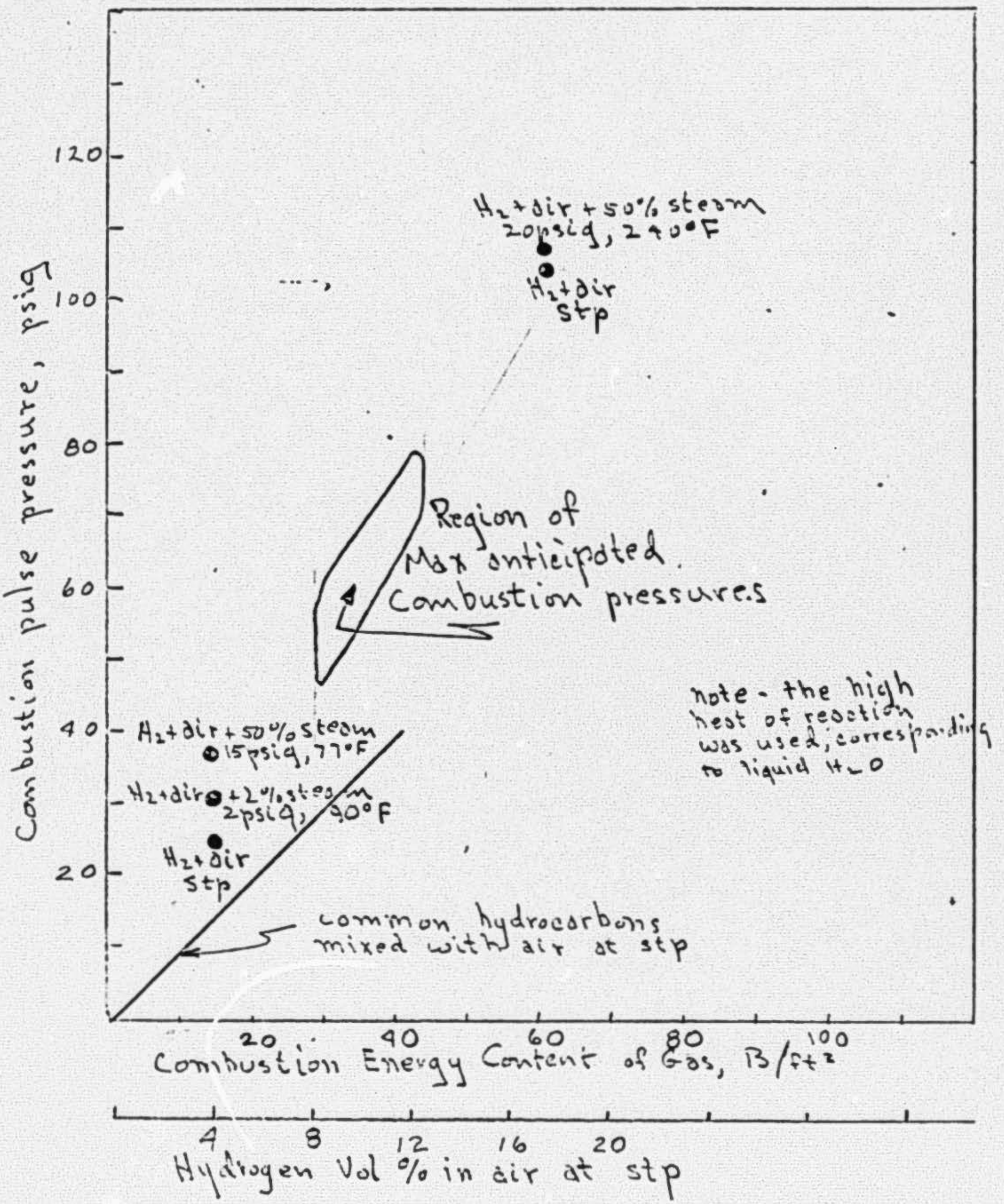

Fig 1. Combustion Pressures

XIII.c. Potential for Steam Explosions

When materials at very high temperatures (e.g., molten UO_2) come in contact with colder liquids there is a potential for a vapor explosion. If the cold material is water the explosion is referred to as a steam explosion. This process results from very high rates of heat transfer forming vapor in an explosive manner and not in a release of chemical energy. Vapor explosions have accidentally taken place in a variety of industries, including nuclear (e.g., SPERT-I, SL-1), as well as under more controlled laboratory conditions involving materials relevant to these industries and with simulant materials for more basic studies of the mechanisms and the phenomena involved. Based on experimental evidence the probability of occurrence of a steam explosion as well as the thermal to mechanical conversion efficiency seems to be affected by how the hot-cold materials are brought together as well as a number of other parameters (e.g., temperature, pressure, ratio of cold to hot liquid, existence of an explosion triggering mechanism, degree of fragmentation, etc.). Fragmentation always follows the interaction of a hot and cold material independent of whether a steam explosion takes place or not. (It is not clear if this is the consequence or the cause of the steam explosion: More probably it is the later.) Post-mortem analysis of industrial accidents and small and large scale explosive experiments show efficiencies varying from much less than 1% to as high as 10 to 20% of the thermodynamic maximum. Based on a larger number of recently performed experiments at SANDIA under NRC sponsorship, the maximum efficiency observed for various compositions of molten corium interacting with water was ~1% with the majority of the tests showing efficiencies much lower than 1%. (The efficiency in the SANDIA test has been defined as the mechanical energy divided by the total thermal energy in the system; thus in terms of the thermodynamic maximum this would correspond to an efficiency of 2 to 3%). Another important factor that affects the dynamics of a steam explosion is the amount of material that can participate in the interaction process, i.e., a larger and more sustained steam explosion could occur if the whole core or at least a large part of it could take place in the interaction. Based on a number of meltdown scenarios evaluated in WASH-1400 (NUREG-75/014) and in the Liquid Pathway Generic Study (NUREG-0440) for reactor geometries somewhat similar to TMI-2, it was concluded that the most probable scenarios leading to a steam explosion would not involve large amounts of materials interacting instantaneously, but the interaction would occur in an incoherent manner over a relatively extended period of time.

In order to scope the effects of a potential steam explosion on the TMI-2 containment, we have assumed* that a steam explosion can take place either inside the lower head of the TMI-2 Reactor Vessel (RV) or somewhere on the floor below the RV following vessel melt-through. Based on the analyses performed in NUREG-75/014 and NUREG-0440 mentioned

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*Recent tests at various Laboratories and Institutes in the U.S. as well as in Europe indicate that it is difficult, if not impossible, to induce a steam explosion in a highly pressurized system.

above, as well as the more recent experiments at SANDIA and elsewhere,** we have generated "damage functions" for both inside and outside the reactor vessel and tested them against the TMI-2 containment. In these analyses we have used the following assumptions:

- Total fuel mass -- 205,250 lbm
- Fuel is at the melting point, 2850°C $\simeq$ 5600°R
- The free volume inside the RV available for a slug to expand is 100 $m^3 \cong$ 3530 ft^3
- The steam explosion takes place at the lower part of the RV and accelerates a slug for a distance of ~22 ft.
- 5% of total thermal energy is converted to mechanical work (This is equivalent to 10 to 15% of the thermodynamic maximum); calculations were also performed for a number of other efficiencies all the way down to 1% (2 to 3% of the thermodynamic maximum).
- All work generated goes into accelerating the slug; this is conservative since no account is taken of any work absorbed by any structural materials inside the vessel
- No heat transfer during the slug acceleration, i.e., isentropic expansion,

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**See letter T. G. Theofanous (Purdue U.) to D. J. Dougherty (NRC) dated October 25, 1978 on "Third CSNI Group of Experts Meeting on Fuel Coolant Interactions and the Science of Vapor Explosions."

Table XIII-2 shows a compilation of work-energies as a function of efficiency and fraction of core mass participating in the interaction process. A number of damage functions (P-V curves) generated with the use of the above discussed assumptions are also provided.

Using the range of work-energies evaluated in Table XIII-2 we have assessed the capability of the TMI-2 pressure vessel head to retain its functional integrity (i.e., does not become a missile) and have concluded that the design of the head bolt system (60 bolts, 6.5 inch diameter made up of SA 540-B23 alloy) has sufficient strength to absorb the impacted energy without gross deformation leading to failure. For example, scoping calculations show that a work-energy of ~150 MJ at slug impact would stretch the bolts ~5.5 inches, which is equivalent to ~15% strain.

TABLE XIII-2. WORK-ENERGY AS A FUNCTION OF EFFICIENCY AND FRACTION OF TOTAL FUEL MASS

A. 5% Efficiency*

% of core mass interacting	Work at slug impact, MJ	Work at 1 atmos., MJ
100	131	7000
75	98.25	5250
50	65.5	3500
25	32.75	1750

B. 1.6% Efficiency*

% of core mass interacting	Work at slug impact, MJ	Work at 1 atmos., MJ
100	42	2260
75	31.5	1695
50	21	1130
25	10.5	565

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*Ratio of Mechanical Energy to total thermal energy (equivalent to a factor of 2 to 3 higher on the thermodynamic maximum scale).

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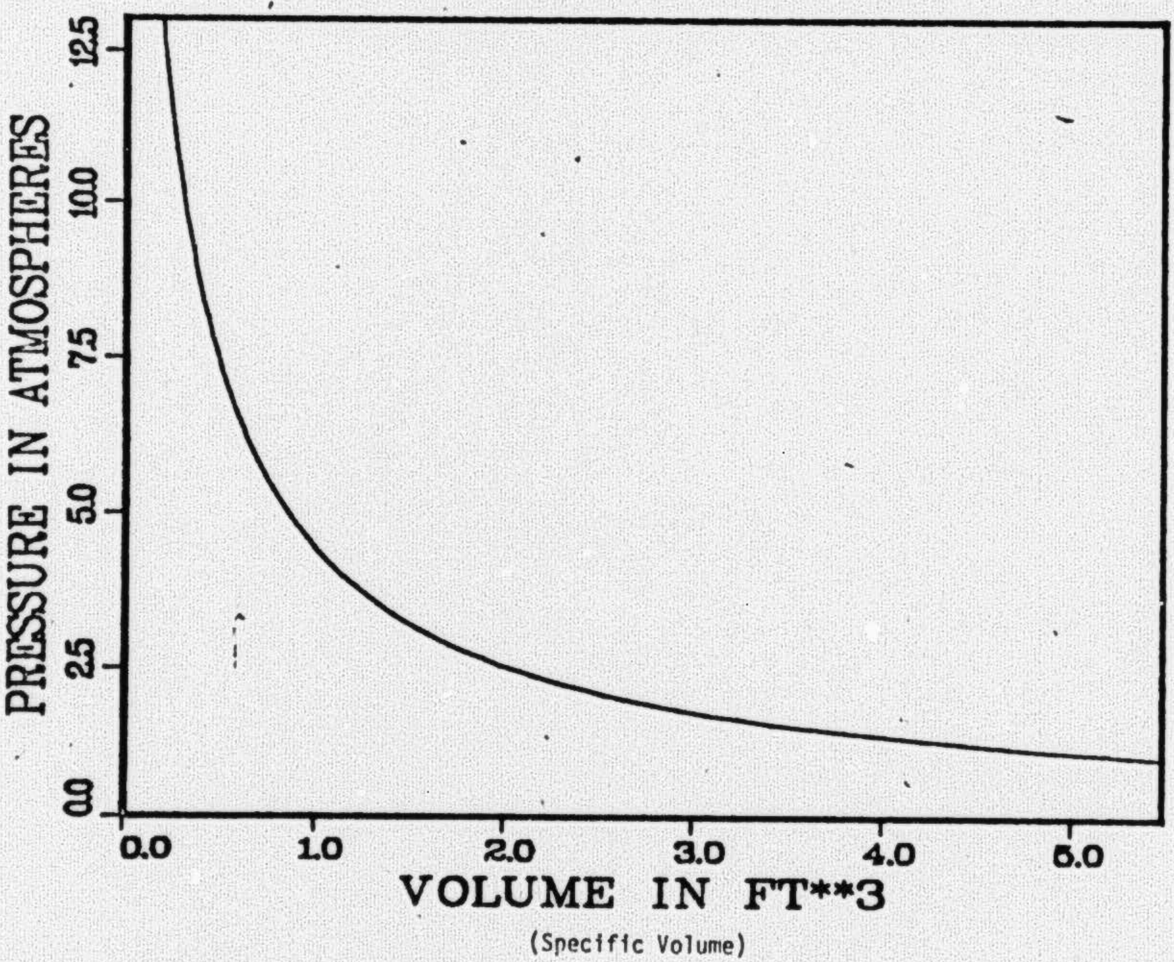
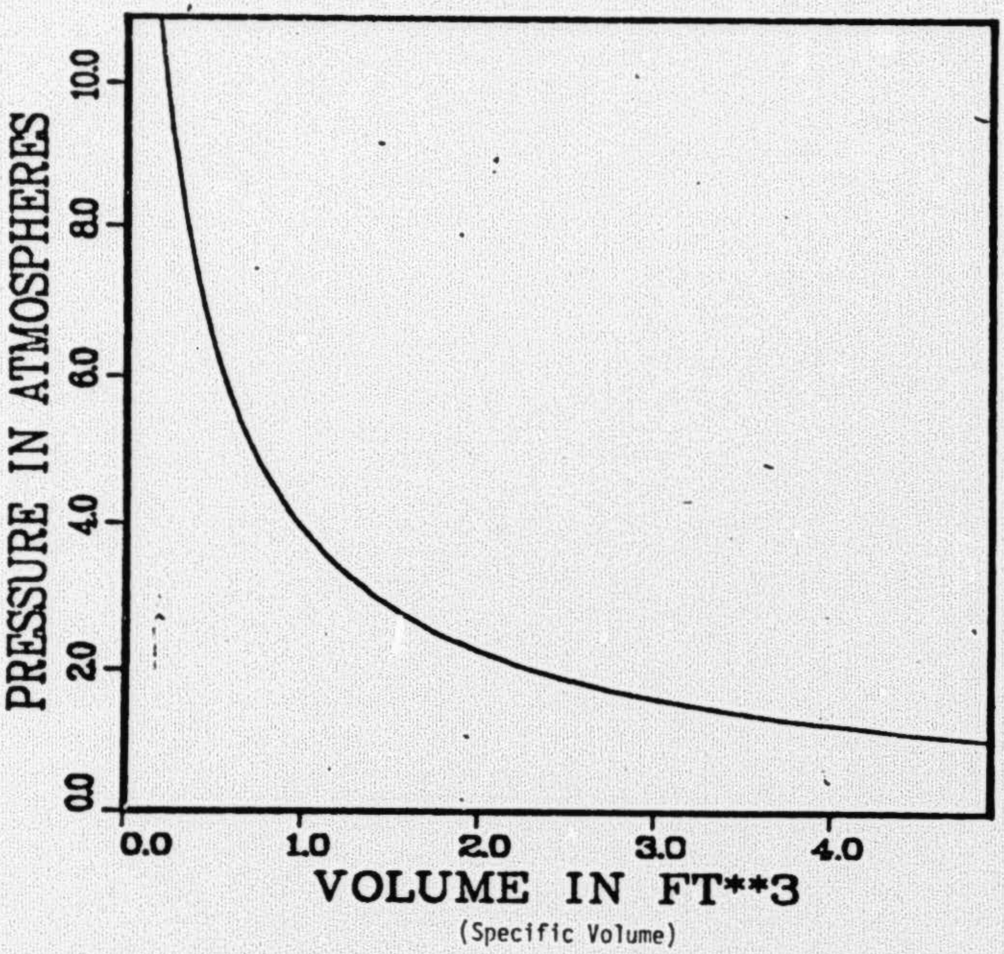
EFFICIENCY = 5%

PRESSURE VS VOLUME



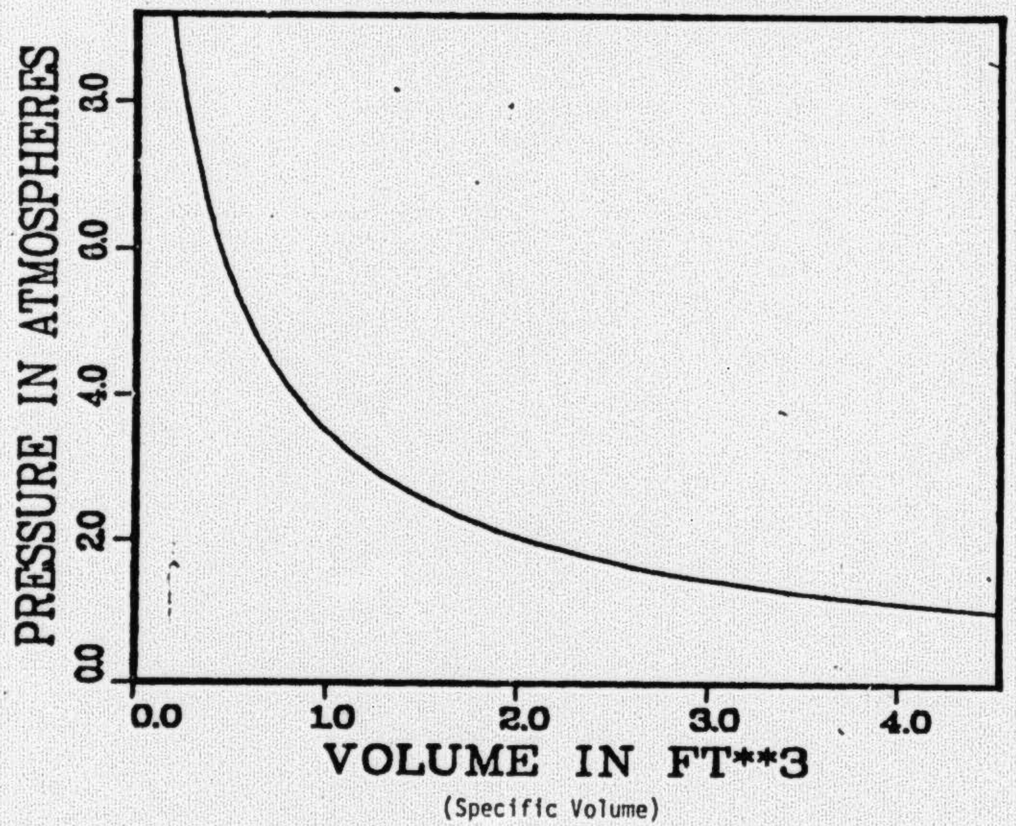
EFFICIENCY = 4.1%

PRESSURE VS VOLUME

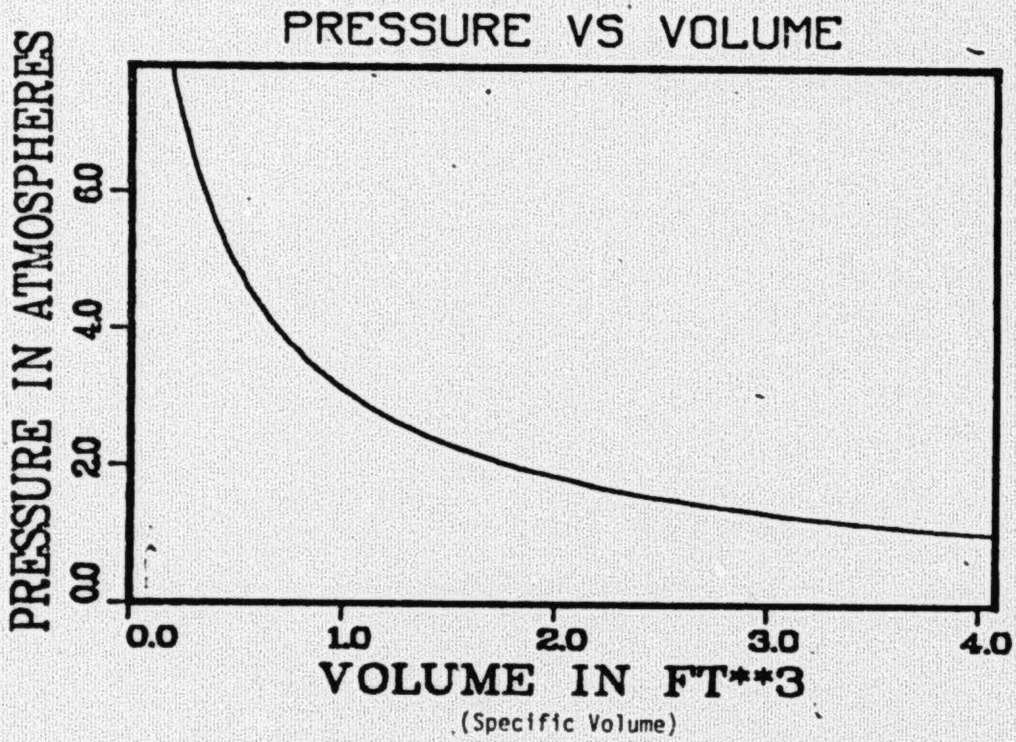


EFFICIENCY = 3.4%

PRESSURE VS VOLUME



EFFICIENCY = 2.7%



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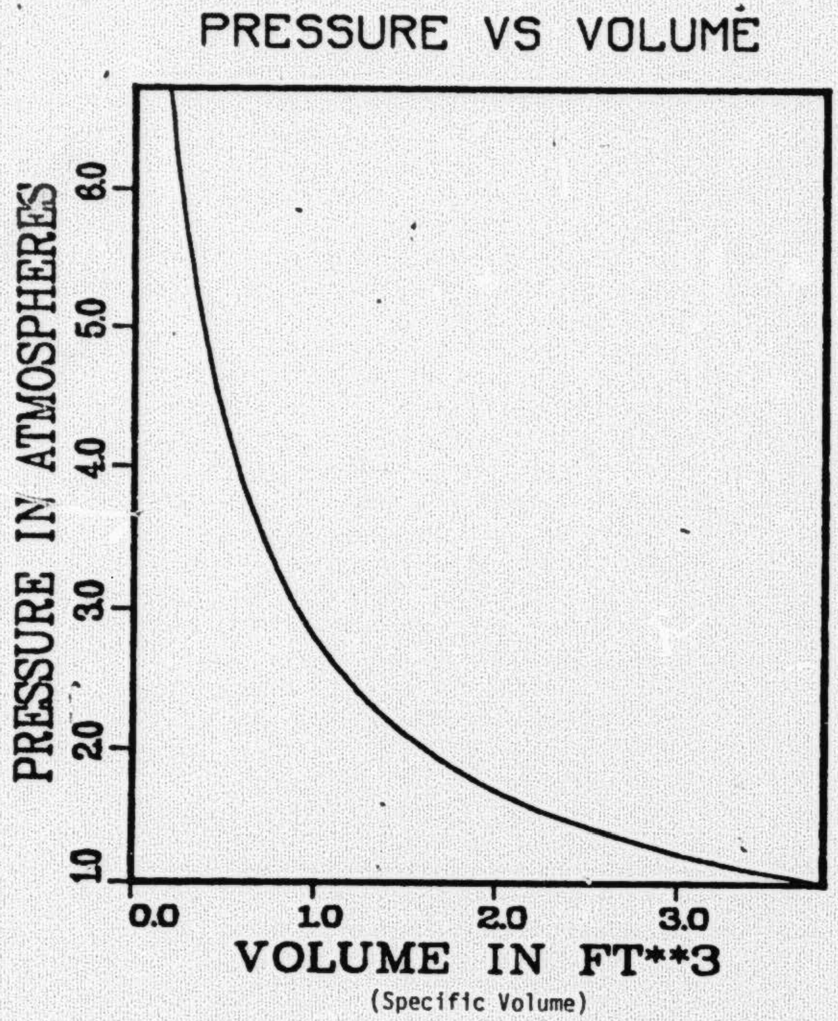
EFFICIENCY = 2.2%



EFFICIENCY = 1.6%

PRESSURE VS VOLUME