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PROPOSED METHODS FOR DEFUELING THE TMI-2 REACTOR CORE

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MASTER

Prepared for the
U.S. Department of Energy
Three Mile Island Operations Office
Under DOE Contract No. DE-AC07-76ID01570

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ABSTRACT

This report constitutes the general concensus of a Debris Defueling Working Group which was established by the U.S. Department of Energy, through EG&G Idaho Inc., to obtain recommendations from nuclear industry representatives concerning techniques for removing fuel debris from the TMI-2 reactor vessel.

The current configuration of the reactor core materials is characterized based on the best information available to the group. The overall core removal philosophy of the group is documented. The type of equipment recommended for core removal is described. The need for development testing to support the design and operation of the equipment is discussed.

FOREWORD

This Rockwell International report, titled Proposed Methods for Defueling the TMI-2 Reactor Core, was first published in May 1983 as a letter report. It is being published as a GEND Informal document to ensure it remains a part of the historical record of the recovery effort at Three Mile Island Unit 2. Its content is based on information available before March 1982 and contains significant assumptions on debris parameters.

CONTENTS

1.0 INTRODUCTION

In February, 1983, Mr. T. C. Runion, EG&G Manager, Waste Immobilization and Reactor Evaluation (WIRE) Program organized a Debris Defueling Working Group.* The objectives of the group were to provide industry and U.S. Department of Energy (DOE) experience and recommendations to General Public Utilities (GPU) on techniques for removing fuel debris from the reactor vessel. Meetings of the group were held at Three Mile Island (TMI) on March 3, March 17 and April 7. A number of proposals and options were considered and evaluated, and a preferred system evolved which represented the general concensus of the group.

A Rockwell Debris Defueling Team** was assembled to brainstorm, investigate alternate approaches and make recommendations. This effort significantly assisted in identifying and characterizing the recommended defueling system.

This report provides information which is believed to best characterize the current configuration of the reactor core. The preferred core removal philosophy developed by the group is presented. A general, conceptual description of the systems and equipment necessary to remove and ship the fuel debris is presented. A number of areas where development effort appears to be necessary or appropriate are discussed.

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2.0 CHARACTERIZATION OF THE REACTOR CORE

The TMI-2 reactor initially contained 177 fuel assemblies which collectively formed an active cylindrical core about 10 feet in diameter and 12 feet high. During the March 28, 1979 loss of coolant accident, the core overheated and a resulting zirconium-water reaction oxidized about 40% of the zirconium in the core.(1) A similar fraction of the in-core inconel and stainless steel components were melted. Most of the stainless steel control rod tubes containing a Silver-Indium-Cadmium alloy overheated and ruptured or melted. Most of the Cadmium vaporized. The molten materials solidified as they fell to the level of the cooling water, forming some particulate and some agglomerate (fuel and debris frozen in the solidified silver, stainless steel and inconel). The initial guidance given to the group concerning core characterization is in Appendix 1.

Estimates of the amounts of the various materials in the degraded reactor system are shown in Table 1. The estimated size gradation and quantities of the loose rubble and fines is shown in Figure 1. The amounts of agglomerate and coarse materials were estimated on the basis of the oxidation and thermal fracturing of 40% of the reactor core zirconium, the thermal fracturing of the related fuel pellets and an estimated balance of the molten materials available to fill the voids in the debris to form an agglomerate. The amount of fines in the system was estimated from an analysis of the particulate deposited on filters and a balance of the Cadmium in the system. It is believed that the core debris did not continue to degrade significantly after the first few days following the accident. The amount of free oxygen in the system would have been used up, by oxidation, then the oxidation processes would stop. There were probably no significant corrosion processes in the cooled system which were reactive enough to remove chemically bound oxygen from the water. If there had been, they would have released significant net quantities of hydrogen, and none was observed. Therefore, the amount and type of fine material in the primary reactor cooling system is probably much the same today as it was after the accident. Some of the evidences that only a relatively small fraction (~1%) of the core material is below about 20 microns (the size below which it is difficult to remove much of the material with the use of large hydroclones) is presented in the following paragraphs.

The "Interim Report on the TMI-2 Purification Filter Examination"(2), Table 6, includes an analysis of 47 of the particles removed from filter MUF-5B. Assuming that the chemical make-up of the particles shown in Table 6 represents the average composition of all particles in the system below about 25 microns, the composite chemical composition of those particles would be about as shown in Table 2.

TABLE 1. Approximate Weight and Volume of Materials to be Removed From TMI-2 Active Core Region.

Material	Total		Intact		Frozen		1 in. to 800μ Rubble		800μ to 4μ Fines		< 4μ Fine Fines	
	kg	L	kg	L	kg	L	kg	L	kg	L	kg	L
Uranium Oxide UO_2, ρ=10	93,400	9,340	56,000	5,600	3,000	300	30,400	3,040	4,000	400	20	2
Zirconium Zr, ρ=6.5	14,200	2,200	14,200	2,200	-	-	-	-	-	-	-	-
Zirc. Oxide ZrO_2, ρ=5	9,500	1,900	500	100	500	100	8,000	1,600	500	100	15	1
Silver, Ind, Cad Ag-In-Cd, ρ=10.2	2,760	270	1,130	110	1,120	110	50	5	400	40	50	5
Inconel 718 ρ=8.2	1,210	150	730	90	130	15	130	15	200	25	20	2
304 St. Stl ρ=7.8	1,610	210	960	125	220	30	210	25	200	25	20	2
Ceramic Pellets $Al_2O_3+B_4C+Gd_2O_3$ ρ=3.45	760	220	460	130	20	5	280	65	-	-	-	-
Total	123,430	14,290	73,980	8,355	4,990	560	39,070	4,770	5,300	590	125	12
% of Total	100.0	100.0	59.9	58.5	4.0	3.9	31.7	33.4	4.3	4.1	0.1	0.1

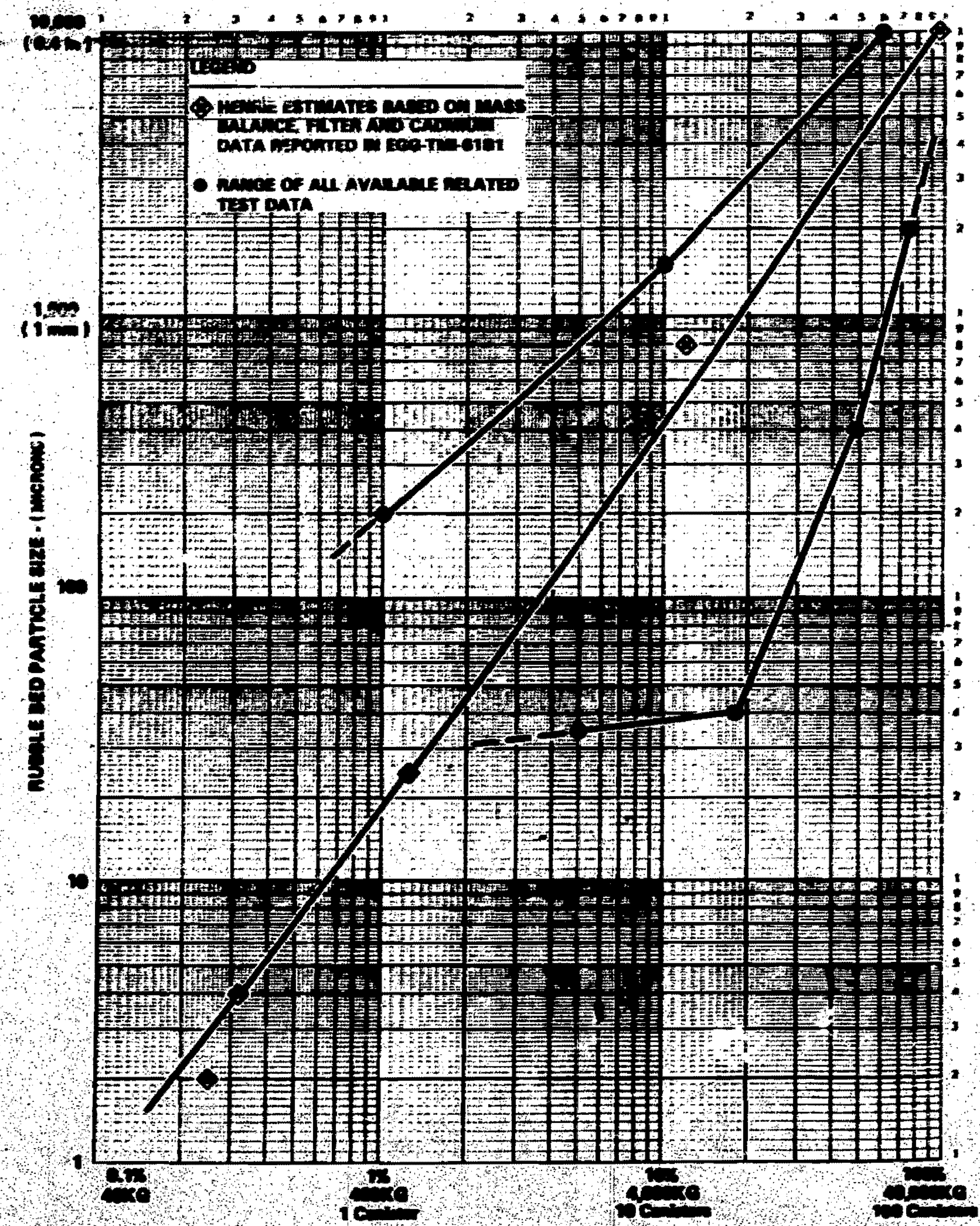


FIGURE 1. Weight %, Weight, and Number of Canisters (at 400kg per canister) of TMI-Rubble Bed Particles less than sizes shown.

TABLE 2. Inferred Chemical Composition of the Composite of Particles Less than 25 Microns.

Element	%	Element	%	Element	%
Mg	8.1	Ag	7.8	Fe	10.0
Al	1.6	Cd	26.9	Ni	10.0
Zr	5.7	In	5.9	Mo	12.1
U	10.8			Cr	1.1

NOTES: 1. Oxygen was not reported.
2. Silicon is excluded since it apparently came from filter fibers.

An analysis of the cadmium in the system was used as the basis for estimating the total quantities of particulate materials in the system. There are 137 kg of cadmium (5% of 2,750 kg of Ag-In-Cd neutron poison material) in the Reactor Cooling System. Assuming that 90% of the stainless-steel cladding around this material ruptured (all but part of the outer row) and that all of the cadmium in the ruptured rods escaped as a vapor, a total of 123 kg of cadmium would have escaped. Further assuming that 90% of this cadmium vapor condensed into fine particles or coated on other fine particles, 110 kg of cadmium would be present as fines.

The analysis of the particles retained on the MUF-5B filter indicates that they contained 27% cadmium. Therefore, the total fines (between about 2 microns and about 25 microns) could be inferred to be ~410 kg.

The volume distribution of particles below 25 microns which were retained on the filter MUF-5B, is shown on Figure 2. This figure was derived from an analysis of the particle size distribution shown in Figure 19 of Reference 2. Even though the reference indicates that approximately 50% of the particles retained were below 4 microns, only approximately 6% of the volume retained was below 4 microns. Note that most of the particles below 2 microns may have passed through the filter. Therefore, it can be inferred that approximately 25 kg of the estimated 410 kg has particle sizes ranging between 2 and 4 microns. To approximate the quantities of particles below 2 microns in the system, the analyses[2] of the coolant sample taken in March 1979 and August 1980, were considered. In the March 1979 sample, the concentration was 68 mg/L. The particle size distribution for that sample indicates a concentration of about 25 mg/L below 2 microns. This extrapolates to less than 10 kg of material smaller than 2 microns suspended in the entire cooling system. Since half of the suspended particles were greater than 5 microns, and since the larger particles have faster settling rates, it is judged that a reasonable fraction, say >10%, of the particles below 2 microns would still be suspended at that time. On this basis, the total weight of materials below 2 microns in the system would be less than 100 kg. The second sample, taken after more than a year of settling, shows a total concentration of 128 mg/L of particles, all smaller than 5 microns and 85% below 1.2 microns. It may be that many of the small particles observed in this sample were caused by

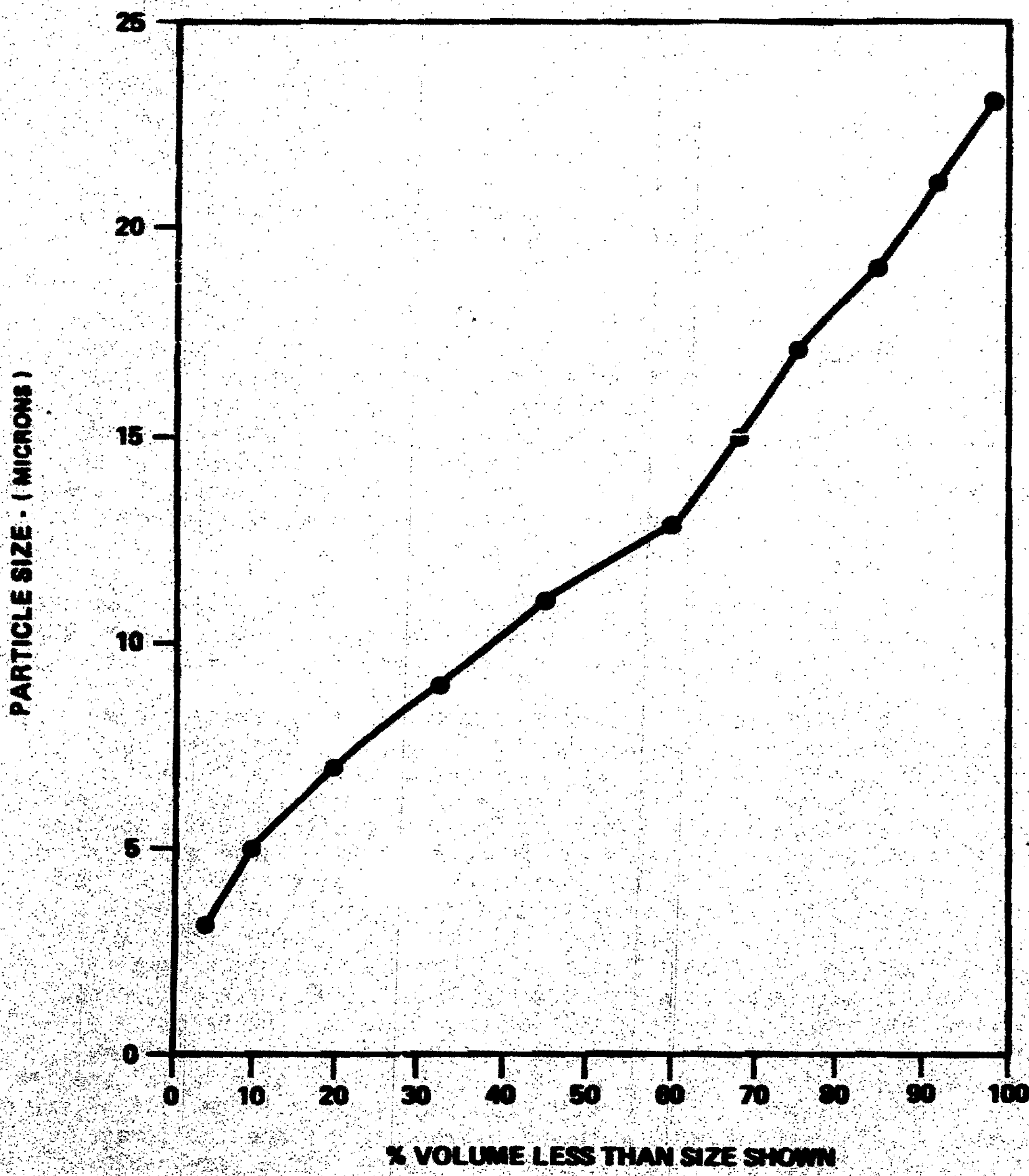


FIGURE 2. Distribution of Particle Sizes on Filter MUF-2B.

oxidation and precipitation of dissolved solids as the sample was brought in contact with air. This sample contained iron oxides, but no silver, chromium, indium, sodium, nickel, tin, or zirconium. (Additional samples should be taken and tests run in air and without air to determine whether fine particulate will be generated in the RCS when the reactor vessel head is removed.) A total of 128 mg/L amounts to about 35 kg of solids in 10,000 ft^3 of coolant. Therefore, to assume that the RCS contains a total of 100 kg of particles below 2 microns appears to be reasonable. This is supported by relatively low quantities of uranium and alpha contamination found in samples taken to characterize the materials being trapped in the sand filters of the submerged demineralizer system (SDS) system. It is also supported as a high estimate by the plot of particle size distribution shown in Figure 1, including the related available test data which shows essentially nothin below 30 microns.

Therefore, it appears that Figure 1 provides a reasonable basis for believing that the particles in the TMI-2 reactor containment system (RCS) which are below about 20 microns might be retained in one or two canisters.

3.0 CORE REMOVAL PHILOSOPHY

A general concensus concerning core removal philosophy has been developed by the Debris Defueling Working Group. The overall objective is to safely remove and ship the core materials within a reasonable schedule and at the minimum overall cost in terms of dollars and personnel exposure to nuclear radiation. To accomplish this requires:

1. The confinement of contamination to the fullest extent practicable
2. Minimizing the total waste volume
3. The use of simplified, well developed, low-maintenance equipment and techniques
4. The use of water as the primary shield to work through
5. Minimizing the build-up of particulates in the water to enhance visibility and to minimize radiation levels at work stations
6. Removing the core debris with the minimum practicable amount of water.

After removal of the reactor vessel head and colandria, the primary defueling activities and the order in which they can best be performed are:

1. Install a cylindrical barrier above the reactor core vessel to avoid contamination of the refueling canal as the water level is raised. Brackets, etc., for locating equipment on the inner wall of the barrier should be included as part of the barrier design. The method for moving fuel canisters over or through the barrier must also be decided in advance and accommodated in the barrier design
2. Using a well developed "hydraulic vacuum dusting" tool, and a particulate separation and removal system to be described later, hydraulically remove the loose fines (below about 500 microns) from the exposed surfaces in the reactor vessel
3. Using extended tongs, pick up exposed loose pieces of rubble which are longer than about 1 in. and place them in a debris bucket
4. Using a well developed jet boosted hydraulic vacuum nozzle, and the particulate separation and removal system, hydraulically remove the exposed loose rubble and fine debris
5. Fracture or cut the exposed agglomerate material into sizes less than about 12 in. Relatively poor bonds should exist between the frozen metal (mostly silver) and the fuel debris. Further, a study of the core temperatures which occurred during the first day

of the accident indicates that the agglomerate is probably not continuous and uniform. Therefore, the use of extended crowbars and jackhammers with spade-like tips may be preferrable (at least for a first try) to the use of power cutting tools in reducing the agglomerate to manageable sizes. As manageable chuncks are produced, they would be canistered and removed

6. Steps 2, 3, and 4 would be repeated as necessary to remove loose particulate and rubble

7. Grapple and remove the fuel assemblies in the outer row which may be intact and not frozen in place. Working inward from the peripherey of the core, loosen the remaining fuel assembly segments, grapple and lift them, place them in fuel canisters and remove them

8. Again, repeat steps 2, 3, and 4 as necessary

9. Extend a long, slim ($\sim$1-1/2 in. dia.) vacuum probe, through the holes in the lower grids to the bottom of the reactor vessel and remove any fuel debris which might have settled there

10. With what should be over 99% of the fuel material removed from the reactor system, it might then be prudent to replace the reactor vessel head, operate the reactor coolant pumps to suspend and entrain loose fine particulate, then filter and demineralize the water by processing a side stream.

4.0 RUBBLE REMOVAL SYSTEM AND EQUIPMENT

It is anticipated that the hydraulically removed rubble and fine particles will be contained in canisters which will be dewatered, gas stabilized by catalyst addition, and mechanically sealed for shipment and storage. The size of these canisters is limited to about 12 in. diameter by 12 ft long. They will each have a rubble capacity of about 400 to 800 kg. On that basis, approximately 50 or 100 canisters would be required to contain the amounts of loose rubble projected in Table 1. Arbitrarily assuming the larger number, it appears from Figure 1 that 85 of the canisters would contain the loose rubble larger than about 800 microns; 14 canisters would contain particles between 20 and 800 microns, and one canister might contain the loose particles smaller than 20 microns. Even allowing for considerable error, it appears that not many canisters would be required to contain the fine materials.

Based on the projected size distribution and the core removal philosophy discussed in Section 3, the hydraulic system recommended for removing the loose rubble smaller than about one inch sizes, is shown in Figures 3 and 4.

The system consists of about four different pick-up nozzles; a knockout canister to remove particles down to about 800 microns; a $\sim$150 gpm pump; two parallel $\sim$6-in. hydroclones--one to remove particles down to about 40 microns prior to returning its water stream to the jet booster pick-up nozzle and the other to remove particles down to about 20 microns in the waste stream going to a hold-up tank; a $\sim$750 gal. hold-up tank; a $\sim$30 gpm pump to keep the water in the hold-up tank agitated and to deliver $\sim$15 gpm to a filter; and an automatically backflushing filter to remove particles down to less than one micron. The filtrate is then passed through the SDS and returned as clear, deionized water to the reactor system at an elevation near the top of the barrier.

4.1 Hydraulic Pick-Up Nozzles

Simplified, schematic sketches of four nozzle concepts are shown in Figures 5, 6, and 7. Figure 5 shows a brush/screen vacuum nozzle to be used to remove loose fines from exposed surfaces. Figure 6 shows a jet boosted nozzle to be used for coarse rubble less than about 1 in. size. Figure 7 shows a small diameter, cylindrical screen and an open nozzle to be used for the same purposes as the other two nozzles, but in tight places, such as under the reactor lower grid plate.

The nozzle shown in Figure 6 is the most complex and will be the most cumbersome to operate since it is more massive and requires two flexible hoses to incorporate the recirculation jet boost feature. The jet boost provides additional head to carry a higher rubble fraction and minimizes plugging in the flexible hose carrying the coarse rubble. The recirculation feature approximately doubles the flow through the hose, allowing a larger flexible hose while still maintaining the velocity necessary to keep the dense rubble moving. If the nozzle plugs at the inlet, the recirculation flow should be sufficient to clear the rubble from the lines--thereby preventing it from falling back to the nozzle.

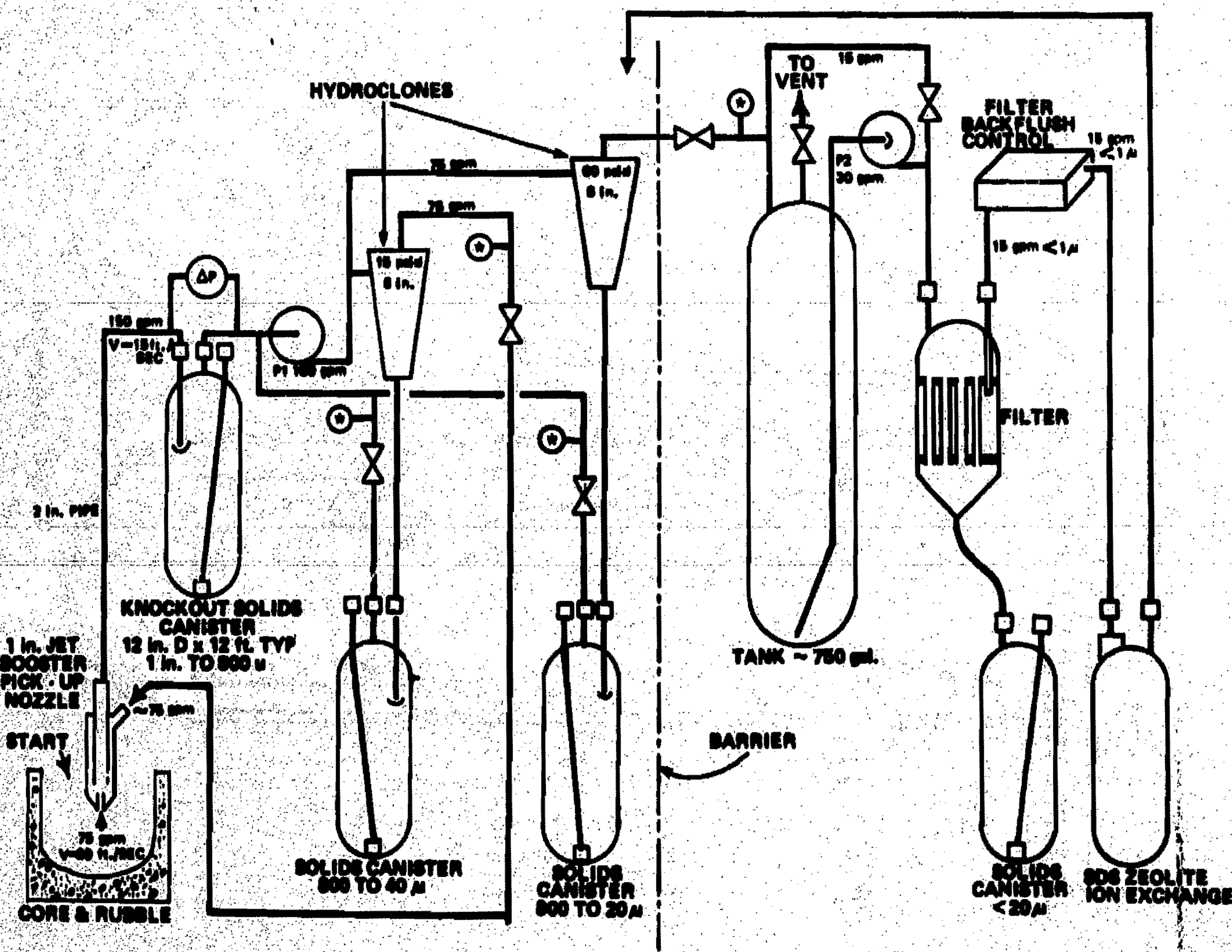


FIGURE 3. Reactor Core Rubble Removal Flow Diagram.

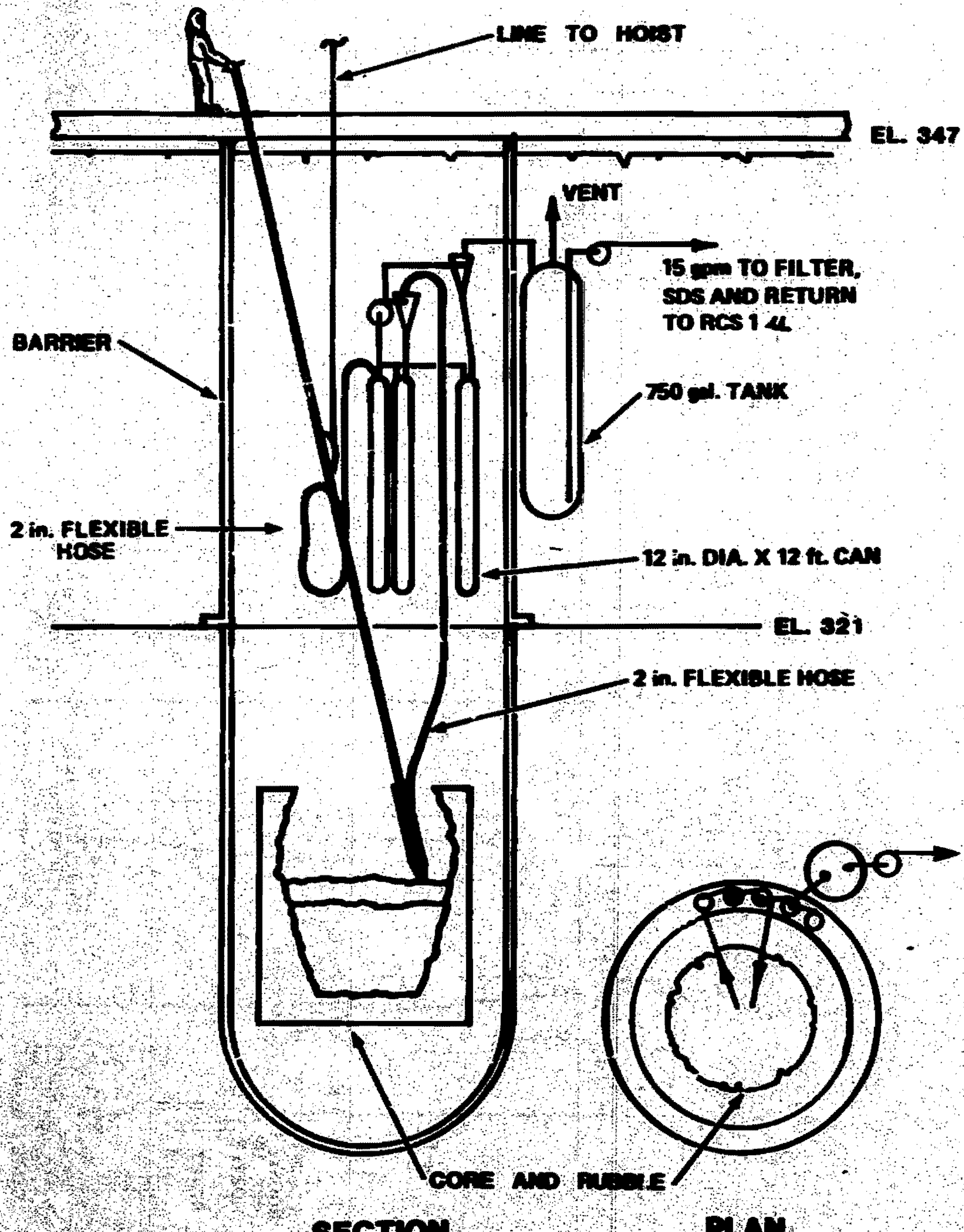


FIGURE 4. Reactor Core Rubble Removal Installation Schematic.

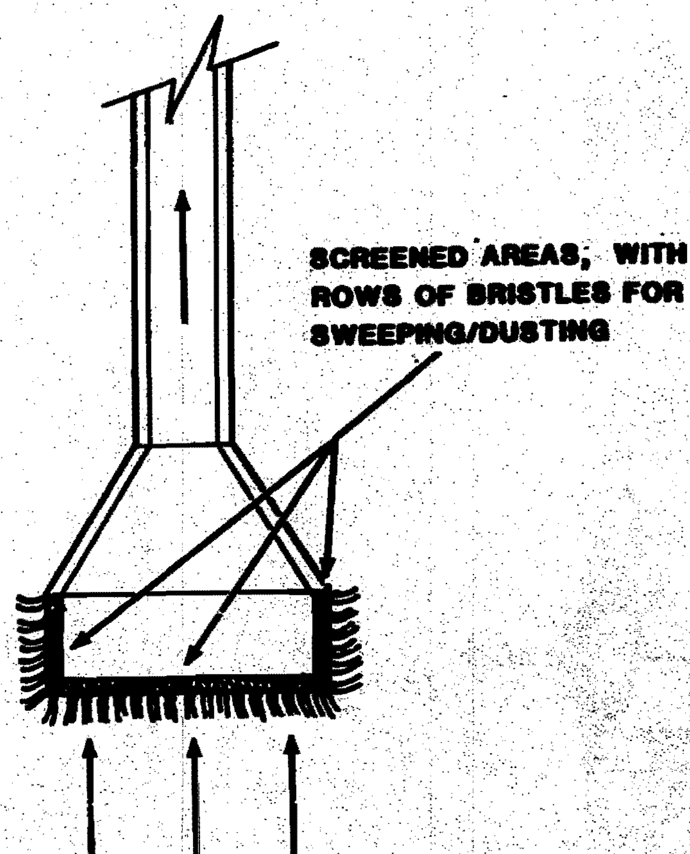
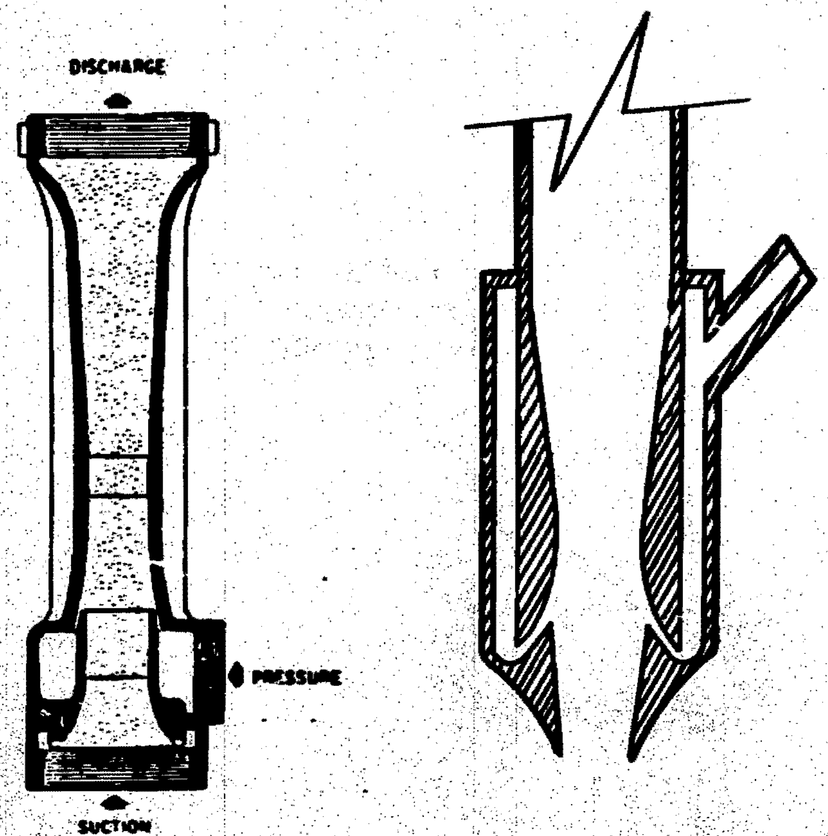


FIGURE 5. Simplified Cross Section of a Brush/Screen Nozzle Concept for Hydraulic Vacuuming Fines from Open, Exposed Surfaces.



A. TYPICAL JET BOOSTER PUMP

B. JET BOOSTER MODIFIED FOR RUBBLE PICK-UP

FIGURE 6. Simplified Cross Sections for Jet Boosted Hydraulic Nozzles.

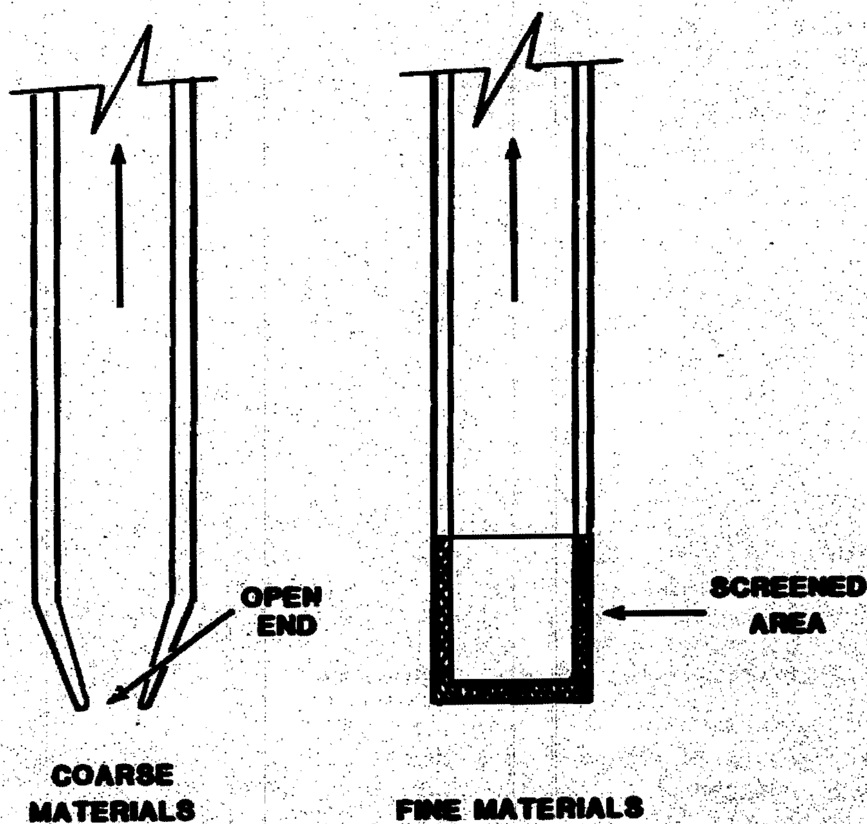


FIGURE 7. Simplified Cross Section of Small Diameter Nozzles for Removing Rubble and Fines from Tight Areas.

4.2 Knockout Canister

The knockout canister is shown in Figure 8. Its purpose is to remove the coarse rubble from the hydraulic stream with minimal headloss. The inlet line exits into the canister through a long radius, 45° elbow to give a tangential component to the flow -- thereby assisting in the gravitational settling of the solids. The termination of the inlet line can be located at the level established for the fuel debris in the canister. As the debris level starts to increase above the desired level, the pressure drop across the canister will increase, signaling that the canister is adequately filled.

It is expected that the knockout canister will remove essentially all of the rubble larger than 800 microns. From Figure 1, it is believed that about 85% (~33,000 kg) of the rubble will be retained in the knockout canisters. The knockout canister contains a dewatering device which consists of a dip tube and filter.

4.3 Pump - P1

This pump is located downstream from the knockout canister and could be of the centrifugal type. Its head and flow requirements will probably be about 100 psi and 150 gpm.

4.4 Hydroclones

Two parallel 6-in. hydroclones appear to fit the needs of the system. A low head loss hydroclone would discharge about 75 gpm to the jet booster. It would remove the particulate down to about 40 microns. The other hydroclone would utilize a higher fraction of the available head, but would be more efficient in removing fines. It would remove fines down to about 20 microns and discharge about 75 gpm to a hold-up tank. From Figure 1, it is believed that the hydroclones will remove about 14% (~6,000 kg) of the loose debris.

Each hydroclone is attached to a debris canister through a flexible line and quick disconnect tool which mates to a Hansen (or equivalent) coupling. If the flexible line is steeply sloped, is short enough, and has a large enough diameter, it might be that no underflow to the debris canister would be necessary. However, based on test results[3] which show decreased performance, including plugging, for low underflow conditions, and considering the difficulty of close coupling the canisters to the hydroclones, provision for underflow recycle is recommended. The level of debris fines in the canisters can probably be determined by the use of a portable gamma ray detecting probe, or a series of detectors located outside the canister at specifically fixed elevations.

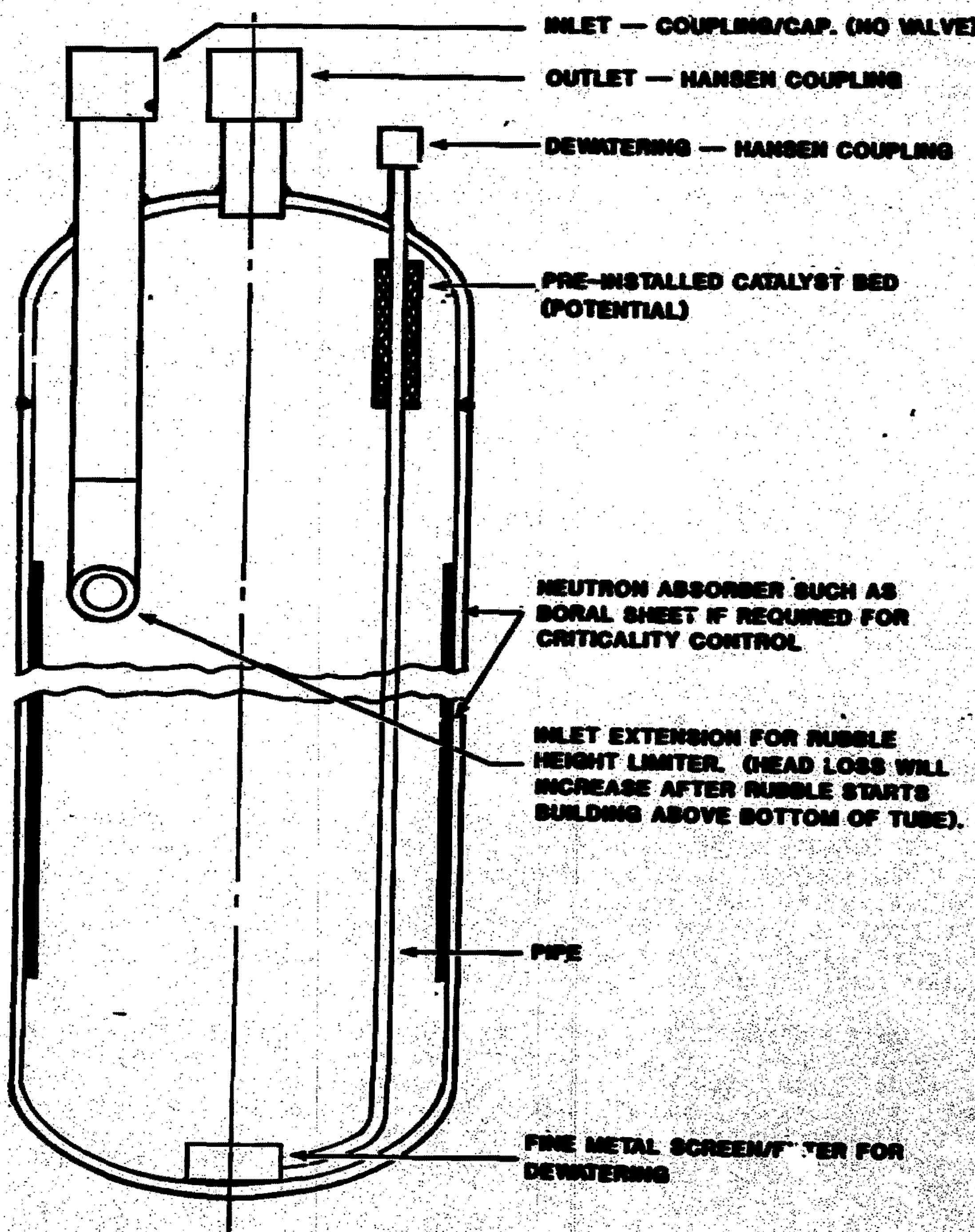


FIGURE 8. Knockout Canister.

4.5 Hold-up Tank

A hold-up tank tentatively sized at 750 gal is proposed to accept the flow from the debris removal system. The minimum flow rate from the removal system appears to be about 75 gpm. The flow rate of the stream leaving the hold-up tank appears to be limited by the final filtration and SDS to about 15 gpm. The hold-up tank size would allow the hydraulic pickup system to operate for about 12 min each hour. (The tank could be eliminated if the filter and demineralizer systems were designed to handle about 75 gpm rather than 15 gpm.)

4.6 Pump - P2

This pump, probably centrifugal, takes water and fine suspended material from the hold-up tank. Part of the output can be circulated back to the hold-up tank to assure that fines remain in suspension. Approximately 15 gpm is directed to the filter.

4.7 Filter and Backflush Control System

The recommended filter system is commercially available, utilizes sintered metal tubular elements as the filter media and utilizes an automatic backflush system to avoid filter plugging. The system shown schematically in Figure 3 is recommended by the Mott Metallurgical Company.

The average flow through a rolled, sintered tube in Mott's model PHP process filter is $\sim$0.5 gpm/ft^2, with tubes 2 in. to 2-1/2 in. O.D., 1/16 in. wall thickness, maximum 6 ft length and 0.5 micron pore size. Tubes are situated vertically in bundles of up to 31 tubes, each.

Solution to be processed would be pumped into the filter apparatus at about 15 gpm and 40-50 psid. When the differential pressure exceeds a predetermined maximum, the filter elements are cleared of caked particles by a high pressure blow-back system. Duration of this purge is usually one second or less, allowing for uniform purge pressure distribution; and complete removal of the filter cake. The filtrate solution is not expected to contain particles greater than one micron.

Figure 3 shows the solids canister separate from the filter. However, if the total quantity of particles less than 20 microns in the reactor system is as low ($\sim$1% or 400 kg) as indicated by Figure 1, the filter should be built integrally into the solids canister. Dewatering of the integral filter-canister would be by upending the canister and removing the water through the filter. Vacuum drying could also be accomplished through the filter.

5.0 DEVELOPMENT

Even though all of the systems and components proposed are considered to be state-of-the-art in the nonnuclear industry, development testing of prototype designs of some of the components (particularly the pickup nozzles) would be cost effective. Cold (nonradioactive) system tests of the developed components, including hydroclone and filter subsystems would also be effective in assuring their operability and in training the operators.

The following development tests are suggested to support equipment design:

1. <u>Pick-up Nozzles</u>

   a) Establish flowrates and velocities required to pick up (as a function of distance between the material and the nozzle) and to suspend coarse solids. Use suitable stand-in material such as lead slugs, in sizes up to 3/8 in. dia. x 1.1 in. long.

   b) Design, build and test a jet booster nozzle, using the output of (a) in establishing flow, head and pipe/nozzle sizes. (See Figure 6.)

   c) Design, build and test a series of nozzles to pick up fine paticles in open and restricted areas. (See Figures 5 and 7.)

2. <u>Knockout Canisters</u>

   Design, build and test coarse and fine knockout canisters (2 in. nozzles and 1/2 in. nozzles) which maximize the collection (settling) of coarse and fine particles. (See Figure 8.)

3. <u>Special Tooling</u>

   Design, build and development test the tooling for:

   a) Attaching to and manipulating the jet-booster pick-up nozzle and the vacuum dusting nozzles. These tools may be an integral part of those nozzles.

   b) Installing canisters, attaching and removing large, ~2-in. and small, ~1/2-in. hose connectors, and dewatering, vacuum drying, adding catalyst, and plugging or capping connections.

   c) Selectively picking-up pieces, or chunks of agglomerate, larger than 1 in., for placing in buckets/cannisters.

4. System For "Wet" Shipping And Storage

a) Determine the affects of borated water and fine particulates on the performance of catalyst preloaded in knock out canisters. This might eliminate the need to add catalyst after canister filling.

b) Repeat the tests in (a) using Canadian-developed, silicon-coated, wet-proof catalyst. This might eliminate the need to vacuum dry the canisters after the initial dewatering and prior to shipment and long term storage.

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