WANL Proposal 67-4
March 27, 1967

Westinghouse Electric Corporation
Astronuclear Laboratory
P. O. Box 10864
Pittsburgh, Pennsylvania 15236

NOTICE

This report contains information of a preliminary nature and was prepared primarily for internal use at the originating installation. It is subject to revision or correction and therefore does not represent a final report. It is passed to the recipient in confidence and should not be abstracted or further disclosed without the approval of the originating installation or USAEC Technical Information Center, Oak Ridge, TN 37830

Records

MODEL EXPERIMENTS FOR E/STS 2, 3
WET DUCT EXHAUST SCRUBBER

MASTER

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

INFORMATION CATEGORY

UNCLASSIFIED

WJ Karener 3/29/67
Authorized Classifier Date

TABLE OF CONTENTS

	<u>Page</u>
I. INTRODUCTION	1
A. Problem Statement	1
B. Background	1
C. Program Summary	2
II. PROGRAM PLAN	3
A. Statement of Work	3
B. Experimental Plan	4
C. Schedule	6
III. TECHNICAL DISCUSSION	8
A. Facilities	8
1. General	8
2. Gas Generator	10
3. Irradiated Sample Module	16
4. Flow Duct	18
5. Elbow	18
6. Dummy Ejector	19
7. Scrubber Model	20
8. Facility Separator	23
9. Water Systems	30
B. System Performance	37
1. Sample Corrosion	37
2. Thermodynamic Behavior	41
3. Radiation Considerations	50
C. Test Plan	52
1. Irradiated Sample	52
2. Flow Experiments	54
3. Scrubber Models	60
IV. REFERENCES	71

LIST OF TABLES

Table No.	Title	Page
I	Detailed Test Plan	5
II	Facility Scrubber Performance	25
III	Summary of Test Operating Parameters	57
IV	Experimental Designs	59

LIST OF FIGURES

Figure No.	Title	Page
1	Program Schedule	7
2	System Schematic for Scrubber Evaluation	9
3	System Scale	11
4	Matching of Gas Heater and Power Supply	13
5	Temperature-Power-Flow Operating Map	15
6	Major Components of the Model Wet Duct System	17
7	Scrubber Shell Concept	21
8	Typical Performance Curves for Commercial Scrubbers	27
9	Water Systems Schematic (Recirculation Mode)	33
10	Water Systems Schematic (One-Pass Mode)	34
11	Average Corrosion Weight Loss Rate for Fuel Elements	38
12	Effect of Wet Duct Water Spray Rate on the Mixture Temperature	42
13	Effect of Scrubber Exhaust Temperature on Total Water Requirements	44
14	Effect of Scrubber Exhaust Temperature on Scrubber Water Requirements	45
15	Effect of Scrubber Exhaust Temperature on Water Vapor Loss in the Scrubber	47
16	Effect of Scrubber Exhaust Temperature on Cooling Load in the Primary Water Loop	48
17	Effect of Facility Separator Exit Temperature on Water Requirements	49
18	Effect of Facility Separator Exit Temperature on the Cooling Load in the Secondary Loop	51
19	Model 1 - Venturi Scrubber	64
20	Model 2 - Spray Scrubber	66
21	Model 3 - Spray-On Cone Scrubber	68

I. INTRODUCTION

A. PROBLEM STATEMENT

A major potential problem in the ground testing of nuclear rocket engines is the release of fission product activity to the Nevada environment and surrounding communities. This problem may become even more acute when nuclear rockets of enormous size are tested in the new Engine System Test Stands (E/STS 2,3). It is therefore necessary to consider the technical concepts required for removing radioactive material of future reactor exhaust gas in order to protect the operating personnel and the public.

B. BACKGROUND

Considerable progress has been made in the past few months with an overall government program consisting of various parties* and facilities throughout the nation. One of the main problems that was recently settled was the development and assurance of a method to cool the torrid rocket gas exhaust to temperature levels where a more simple and rugged duct and collection system could be used and maintained. Scale model testing at AGC and WANL has demonstrated, with reasonable assuredness, the feasibility of the "wet duct" concept. This concept involves the introduction of sufficient quantities of water into the extremely hot hydrogen stream exhausting from a nuclear rocket engine to reduce the bulk temperature to levels where cooling of the duct walls and other component parts is not required.

The area of greatest concern that now remains is the investigation and design of an effective radioactive gas scrubber and particulate collector. From a biological hazard standpoint, radioactive iodine and its precursors, tin, antimony, and tellurium are the undesirable contaminants that have deposited down wind from the reactor effluent cloud, and must now be collected. To collect this particulate, the Marquardt Corporation has made a preliminary evaluation and has recommended the use of a gas scrubber system.¹

*SNPO, AGC, WANL, Marquardt, and Greyrad.

However, the "state-of-the-art" of scrubber use in combination with the "wet duct" concept is not sufficiently advanced to expect a design effort alone to produce an adequate geometry. A program to supplement the design effort through scale model experiments and analysis is required.

C. PROGRAM SUMMARY

The Westinghouse Astronuclear Laboratory Proposes to conduct small scale model wet elbow-scrubber tests (1/40 scale) in its hot hydrogen test facility at Large, Pennsylvania. Results that can be expected from these tests include:

1. Determination of an effective type of scrubber and its efficiency for nuclear rocket exhaust contamination collection.
2. Acquisition of design scale-up information and definition of critical hot spot areas by an early analysis and evaluation of related potential full scale scrubber problems.
3. Evaluation of a complete exhaust cooling and recovery system (1/40 scale) with its interrelated problems.
4. Collection of nuclide deposition data on the walls of the elbow, ejector, scrubber as related to hydrogen gas velocity, water injection, gas temperature, wall temperature, pipe length, and diameter.

In carrying out its part of the analysis and test work, WANL expects to work closely with the Systems Nuclear Propulsion Office, other companies, and facilities involved in the overall program.

II. PROGRAM PLAN

A. STATEMENT OF WORK

Under the terms of this proposal, Westinghouse proposes to furnish the necessary personnel, facilities, supplies and equipment to experimentally evaluate three scaled model scrubbers to provide design data for use in designing the scrubber for the E/STS 2, 3 wet duct exhaust and altitude simulation system.

Task I - Design, Procurement, Installation of 3 MW Facility

A facility will be designed, procured, and installed. This facility will consist of the various components required for a flow system intended to provide radioactive fission products in a high temperature hydrogen gas stream to simulate the conditions in the gas exhausting from the NERVA engine.

Components that will be a part of this system are: a 4500° R hot gas generator, an irradiated fuel sample, convergent-divergent nozzle, diffuser section, right angle turn using a wet elbow, simulated steam ejectors, "absolute" facility gas cleaner, and water systems for cooling and gas scrubbing. The system will also provide a means of inserting experimental models of the gas scrubber to be evaluated for use in the E/STS duct.

Task II - Evaluation of Scrubber Models

Three scrubber models employing three concepts will be comparatively evaluated under test conditions similar to a NERVA engine with full power engine pressure and temperatures. Hydrogen flow will be based on a 1/40 scale model. Other operating parameters effecting scrubber performance will be held constant to provide an identical set of conditions at which the comparative evaluation will take place.

Task III - Parametric Evaluation of Most Promising Scrubber Concept

A series of designed experiments will be employed to optimize the performance of one scrubber by determining the influence of important parameters on scrubbing efficiency. Efficiency will be defined as that proportion of initial activity entrained in the scrubber system.

Hot hydrogen gas flow will be set at a value scaled down from the design flow of the E/STS 2, 3 system but will duplicate the conditions of temperature (4500°R) and pressure. Independent scrubber parameters that will be evaluated are: inlet radioactive species characteristics and flow rate (by use of coated and uncoated irradiated samples of two different lengths) and scrubber outlet temperature. Other dependent variables will be recorded and studied. These include water flow rates and pressures; gas flow rates, pressures, and temperatures; test duration; power input; and others.

Task IV - Data Reduction, Analysis, and Presentation

Data will be recorded continuously during all tests. Data will be reduced, analyzed and presented in a form suitable for distribution to all interested agencies. An interim and a final report will be prepared and distributed as directed.

B. EXPERIMENTAL PLAN

A summary of the detailed experimental plan is presented in Table I. A total of sixteen tests are planned.

Under Task I the 3 MW facility will be modified with the required new equipment being installed. Following this, two tests, a cold and hot hydrogen gas flow check-out will be conducted. Maximum required water rates will be used to verify system capabilities. Procedures will be established for the conduct of the comparative test evaluations of the three scrubber models wherein irradiated fuel samples will be introducing radioactive fission products into the exhaust for removal by the scrubber.

Under Task II these scrubber models will be procured and comparatively evaluated. Six tests are planned, all at one test point. After running one test on each of the three models, a repeat test will be performed on each model at later dates to confirm the results of the first tests. Decontamination of all ductwork and water systems will be required following each test.

TABLE I
DETAILED TEST PLAN

Task No.	Task	Exper. No.	Purpose	----- Scrubber -----			Gas Gen. Out Temp. °R	-----Fuel Sample -----		
				Config.	H ₂ O Rate gpm	Out Temp. °F		Coated	Irradiated	Length in.
I	3 MW Facility	1	Check-Out (Cold)	M ₁	320	70	70	No	No	4
		2	Check-Out (Hot)	M ₁	320	120	4500	No	No	4
II	Test 3 Scrubber Models	3	Comparative Evaluation	M ₁	215	140	4500	No	Yes	4
		4	Comparative Evaluation	M ₂	215	140	4500	No	Yes	4
		5	Comparative Evaluation	M ₃	215	140	4500	No	Yes	4
		6	Comparative Evaluation	M ₁	215	140	4500	No	Yes	4
		7	Comparative Evaluation	M ₂	215	140	4500	No	Yes	4
		8	Comparative Evaluation	M ₃	215	140	4500	No	Yes	4
III	Test Best Scrubber	9	Parametric Study	M	320	120	4500	No	Yes	4
		10	Parametric Study	M	320	120	4500	No	Yes	8
		11	Parametric Study	M	140	160	4500	No	Yes	4
		12	Parametric Study	M	140	160	4500	No	Yes	8
		13	Parametric Study	M	320	120	4550	Yes	Yes	4
		14	Parametric Study	M	320	120	4550	Yes	Yes	8
		15	Parametric Study	M	140	160	4550	Yes	Yes	4
		16	Parametric Study	M	140	160	4550	Yes	Yes	8

Under Task III, eight tests are planned on the most promising scrubber concept. The parameters to be varied will be scrubber outlet temperature (by means of scrubber water flow) and radioactive contaminant loading. The latter will be accomplished by using coated and uncoated irradiated samples of two different lengths. In this manner the rate of radioactive contaminants mass flow (scrubber loading) released per unit time will be varied. Results of these tests will be used to optimize performance, that is, scrubber efficiency.

C. SCHEDULE

The proposed schedule is presented in Figure I. This reflects a facility design, procurement, and installation time of eight months, with a scrubber design and procurement cycle running concurrently. Facility check-out and the experimental evaluation of three scrubber models will follow during the next eight months (9 through 16), with one test scheduled per month. The parametric evaluation experiments will be conducted in the last five months (17 through 21) with one to two tests scheduled per month. This accelerated testing of two tests per month should be attainable due to the experience gained during the first tests. It should be noted that even though models will not be changed in this phase, the disassembly and decontamination of all exhaust ducting will be required between each test.

Data reduction and analysis will be performed following each of the tests. A final report will be submitted at the end of the twenty-fourth month.

FIGURE 1
PROGRAM SCHEDULE

III. TECHNICAL DISCUSSION

A. FACILITIES

1. General

The facility discussed in the ensuing sections describe the various components shown in Figure 2 which are required in the flows system intended to provide radioactive fission products in a high temperature gas stream. The radioactive gas stream is used as a reference on which the performance of scrubber models are based. Following the scrubber model a facility decontamination section removes all residual contamination.

The source of the radioactive fission products is a hydrogen gas stream heated convectively as it passes over electrical resistance heater elements and subsequently passes over an irradiation sample containing the fission products. Various chemical, thermal, pyysical, and mechanical mechanisms permit the hot hydrogen stream to accumulate the fission products. Chemically, hydrogen can react to form $C_p H_m X_n$ compounds where X can be a radioactive material capable of forming modified hydrocarbon type compounds. Thermophysically, diffusing processes using either thermal or concentration gradients would drive fluid fission products into the hydrogen gas for entrainment. Mechanically, radioactive fuel particles and other solids could be entrained by progressive surface erosion permitting the release of solid particles.

The system consists of the following basic components.

- a. The gas generator or six element furnace where the hydrogen gas is heated to temperature identical to those in the NERVA exhaust.
- b. The irradiated fuel sample where the gas stream is provided with fission products to simulate the reactor.
- c. The exhaust flow system containing the convergent-divergent nozzle representing the engine exhaust nozzle, the diffuser section replicating the vertical portion of the test duct, and the right angle turn using a wet elbow.

611659-7B

FIGURE 2
SYSTEM SCHEMATIC FOR SCRUBBER EVALUATION

d. The steam ejectors which would provide the low pressure in the full scale duct during startup and shutdown. In the model duct no provision would be made to supply steam, but the multiple passages of the ejector system would be provided.

e. The scrubber model or the test article of this investigation. A duct with a water supply and return is the basic unit in which various models of scrubbers can be evaluated.

f. The facility gas cleaner, a large particulate and gaseous absorber which insures the maximum removal of the remainder of the radioactive material not collected by the duct model scrubber.

g. Water systems for scrubber injection, wet duct injection, cabling, and facility scrubbing requirements.

The components of this system which are of primary interest in terms of applicability to the design of E/STS 2, 3 would be primarily the scrubber, and secondarily, the wet elbow used in the flow system. Both of these components would be evaluated for material temperature and residual plate-out of solid particulate matter. In addition, the scrubber would be evaluated for its effectiveness in removing radioactive material.

This rather complex system of components is illustrated schematically in Figure 2. This shows the proposed layout of the major components of the experimental apparatus. Figure 3 gives some of the actual physical sizes of these components for a proper visualization of their extent. These sizes are subject to some refinement; however, at present they are based on a linear scale factor of 1/40. This factor as well as the system components will be discussed in detail in the following sections.

2. Gas Generator

The gas generator, which would provide the hot hydrogen supply for the experiments proposed to evaluate the behavior of test duct scrubbers, will be optimized to utilize the maximum electric power output of existing facilities. The power supply presently installed and available at WANL has the following capability:

FIGURE 3
SYSTEM SCALE

2.2 MW for continuous use.

2.8 MW for a continuous duty cycle of 20 minutes per hour.

3.0 MW for short duty cycles followed by long cooling periods.

The temperature rise of the components of this power supply is the limiting factor so that by careful monitoring of temperature, no difficulty is expected in operations at power levels even in excess of 3 MW. The power supply is an assembly of four separate systems which can be connected in three ways. These multiple connection possibilities yield the following nominal voltage current capacities:

Parallel connections

Voltage range 8 to 80, current limited to 35,000 amperes.

Parallel-Series connections

Voltage range 16 to 160, current limited to 17,500 amperes.

Series connections

Voltage range 32 to 320, current limited to 8750 amperes.

These nominal voltage-current maxima will yield a power consumption of 2.8 MW providing that the applied load resistance is such as to require the maximum voltage and current available.

The gas heating tubes consist of a number of individual holes in a graphite rod suitably coated to inhibit hydrogen attack. These gas heaters are replicas of the fuel elements used in the reactor and differ from the reactor fuel element only in the lack of nuclear fuel. Typically such elements have a resistance of 0.05 ohms. These elements serve as the thermal energy source to heat the hydrogen.

In order to obtain the best match of the gas heater with the power supply, Figure 4 was developed which shows the limiting voltage current envelope for the various modes of the power supply as well as the voltage-current requirement of the gas heater connected in parallel. Here the maximum voltage available, as a function of the current, is shown for each of the three modes of operation. On this same curve, the voltage-current characteristics

SLT/A
 FIGURE 4
 MATCHING OF GAS HEATER AND POWER SUPPLY

of one to seven elements, connected in parallel, are shown. That is, the voltage-current curve of the elements goes through the maximum point of the operating envelope of the power supply. For example, as shown, the series parallel connection peaks at a maximum power dissipation of approximately 2.8 MW at 160 volts and 17,500 amperes. This is mid-way between 5 and 6 elements connected in parallel. Four elements in parallel have the power capability reduced to 2.2 MW; three elements in parallel could utilize less than 2 MW. Hence the ideal match between the available power supplies and the gas heaters would be a cluster type of configuration utilizing six elements with a current requirement of approximately 19,000 to 20,000 amperes, slightly in excess of the nominal rates capacity of the unit but well within the ability to reach the requirement of 3 MW.

The configuration of such a gas generator would suggest six multiple heated graphite rods suitably coated with the hydrogen diffusion inhibitor used in the NERVA reactor. This configuration would then permit a relatively conservative operation of each heater element and would further insure the highest probability of tests lasting as long as one hour. Previous experiments have shown that the use of unfueled heater elements provides considerably greater margin of operation over nuclear fueled elements and since the flow in each heater tube would be considerably less than that normally expected in the element, the prognosis of one hour tests or longer is not unreasonable for a six element configuration.

The linear scale factor is defined as the square root of the flow area; that is, if the scale factor is 60, the flow area is 3600 which means that the model is scaled down to a cross section of $1/3600$ of the actual test duct or $1/60$ of the linear dimension. Figure 5 presents the limitation imposed by power supply on the linear scale factor of the model to be used and the gas temperature. With an optimum design of the gas heater to take advantage of the maximum capability of the existing power supply presently installed at WANL, Figure 5 indicates that a scale factor of 42 (approximately 40) at a temperature of 4500°R could be easily obtained. This rather conservative approach would provide operations at temperatures approaching 5000° for the same scale factor at the maximum system capability estimated at 3 MW. It should also be pointed out that scale factors as low as 25 to 1 could be obtained

in the period from 1969 onward when the Waltz Mill capability presently planned for 6 to 7-1/2 MW is installed. This is labelled as the 1969 WANHES Capability on Figure 5. The WANL flow limit line at approximately 38.5 scale factor is a flow limitation imposed on the WANL flow capability of approximately 0.2 pps. This flow limitation is imposed on the surroundings of the test cell at WANL from safety considerations.

The six heaters will be installed in a pressure vessel mounted vertical in order that any gravitational effects existing in a prototype would also occur in the proposed configuration. No major problems are expected with this type of operation since the Thermo-Flow Laboratory has operated many routine tests utilizing a full reactor cluster for reactor assembly evaluations during the past year at power levels and flows approximating those discussed above. A modified design of the existing six heater configuration will be used. In this manner, the maximum available experience from the existing cluster experiments can be factored into the redesign in order that a reliable and yet simple high temperature gas source will be available for the scrubber experiments on the scale test duct.

3. Irradiated Sample Module

The sample module will consist basically of a water cooled, jacketed pipe chamber externally encapsulated with a one inch thick layer of lead radiation shielding. The assembly is illustrated in Figure 6. The unit will be designed for quick installation and removal. Before the module unit is taken to the test cell, a two to eight inch long segment of an irradiated NERVA fuel cluster will be inserted in an ATJ graphite receiver (coated with a thin layer of niobium carbide) contained in the pipe chamber. This operation will be performed in a shielded dry box to eliminate radiation exposure. The carbide coating will prevent contamination of carbon from the graphite receiver with the fission-carbon products eroded from the irradiated sample. At the module exit, a thermocouple and a side port entrance will measure temperature and pressure, respectively. These are two parameters which will be controlled during the experiments.

611659-2B

FIGURE 6
MAJOR COMPONENTS OF THE MODEL WET DUCT SYSTEM

4. Flow Duct

Following the sample module, a similar water cooled jacketed spool piece will be bolted in series as shown in Figure 6. Contained within this section will be two graphite niobium carbide coated components on a 1/40 scale which will make up the flow duct. The first component is a simulated convergent-divergent nozzle. This geometry will use a 0.433 inch nozzle throat diameter followed by the divergent section of the nozzle. The niobium carbide coating will serve to retain the nozzle configuration at the high corrosive temperature and supersonic conditions.

Immediately following the nozzle the hot gas will flow into the supersonic diffuser component (graphite NbC coated) followed by a straight pipe section with an L/D of 4. At the end of this diffuser, the passage again will diverge to a subsonic diffuser resulting in a relatively low velocity, Mach 0.3. The last divergent section in the test duct, shown in Figure 6, will be followed by a sudden expansion resulting from the enlarged diameter plenum section in the elbow.

It is planned to measure the temperature gradient in the walls of the diffuser section. This will be used to calculate the heat flux for design of the full scale diffuser.

5. Elbow

Figure 6 also depicts the wet elbow configuration. This chamber will be made of commercial mild steel. It will be instrumented to obtain critical temperature distributions and pressure information at various positions in the chamber. Surface temperature data will also be accumulated through sensors in the metal walls.

For the purpose of this proposal, a peripheral radial water injection into a large diameter elbow plenum is presented. However, at the time of final test design, the latest elbow configuration can easily be substituted.

It is planned to radially inject water through at least eight spray orifices in an area immediately following the divergent diffuser section. Three circumferential rows having

different sized orifices will also be considered. The water will flash cool the hot hydrogen gas from about 4500°R to about 1000°R. This will permit the carbon steel duct impact area (immediately below the plenum area) to withstand these operating conditions. In this impact area, data such as metal fatigue, corrosion, pitting, rockwell hardness, and other metallurgical properties can be obtained if it is considered necessary to assist in final design of the full scale elbow.

At the downstream end of the elbow, a settling trap will catch heavy particles before entering the volume-restricted ejector chambers. These particles will be washed down through a pipe duct to a barometric well. Washing and quantitative sample collection will take place after the test.

6. Dummy Ejector

During the reactor start-up, an ejector using steam or another gas as a driving force is necessary to provide simulated space vacuum conditions in the nozzle and reactor. At full or nearly full engine power operating regimes, the diffuser itself provides the vacuum environment around the reactor. Consequently, during normal steady-state operation, the ejector steam will be shut-off and the ejectors will serve merely as ducts.

In view of the complexities and high costs of providing the steam required for even the 1/40 scale model, no attempt will be made to simulate the operational steam ejectors. The dummy ejector system will therefore consist of a geometry simulating the ejector ducts and venturis and will act only as a means to transport the gas to the scrubber.

The dummy ejector will be made of mild steel consisting of four parallel tubes flanged at both ends. This is not considered detrimental in that the simulation of the important entrance and exit plenums on either side of the ejectors will be maintained. Pressure drop can, of course, be made similar to that in the E/STS ejectors by proper sizing of the dummy ejector tube diameters and by proper lengths and cone angles on the divergent section.

7. Scrubber Model

One of the primary goals of this program is to study the performance of the wet duct scrubber concept for power levels near 3.0 MW consistent with the 1/40 duct model. The scrubber system for the E/STS facility will be required to remove radioactive substances, both gaseous and particulate matter, from the exhaust stream of the wet duct before flaring of the gases. In order to design an adequate scrubbing system for this purpose, realistic data must be made available from a smaller scale to define the important design parameters for the full scale unit.

The scrubber model will be studied from two points of view in the program. First, the performance of various scrubber concepts will be evaluated under the same conditions of gas flow rate, temperature, pressure, radioactive matter concentration in the gas, and other important parameters in order to select the most promising design concept. Second, the most promising design concept will be evaluated under varying conditions of operating parameters in order to provide scale-up design data for the E/STS scrubber system as well as to explore the operating response surface to define the conditions under which optimum performance can be expected to occur.

In order to accomplish both of these experimental objectives, it will be necessary to provide a flexible mechanical model which can be changed rapidly and efficiently from one concept to another. To the extent permitted by the mechanical requirements of the scrubber concepts selected for experimental evaluation, this will be accomplished by employing a basic envelope or outer shell which will house various internal scrubbing experiments in turn. The internal equipment for the various concepts (for example, venturi scrubbers, vane scrubbers, and impingement baffles) will be removable and will have common mounting assemblies to permit relatively facile attachment to the inside of the scrubber shell. Figure 7 is a sketch of one method by which such an assembly can be made.

Employing a more or less permanent housing for the scrubber experiments will provide the least expense in equipment costs since only one such pressure vessel will be

FIGURE 7
SCRUBBER SHELL CONCEPT

611659-98

required for most of the scrubber concepts which currently appear feasible for E/STS. This conclusion is based on the observation that a horizontal, cylindrical envelope appears most feasible for the underground E/STS installation.

In addition to lower cost and efficient change-over from one scrubber apparatus to another, this common outer shell concept has another advantage. The instrumentation, control leads, and scrubber water lines to and from the scrubber can remain more or less permanently attached to the shell. A substantial amount of hook-up time can be saved. In addition, more reliable operation of all systems can be expected with minimum handling. Further, the use of an internal liner as shown in Figure 7 will contain the fission products which plate out on the scrubber walls. Quantitative sampling will be facilitated and contamination will be minimized.

The shell body itself will be composed of a carbon steel schedule 40 pipe section, flanged at both ends. The flanges will mate with the outlet flange of the dummy ejector section and the inlet flange of the facility separator section. The water manifold for the scrubber experiments as well as the instruments such as thermocouples used in monitoring scrubber operation will penetrate the vessel through a special instrumentation ring attached to the forward flange. It will also be necessary to provide additional penetrations of the vessel through the cylindrical shell and the aft flange for water outlet connections and exit gas instrumentation.

The model scrubber diameter and length will be based on two considerations: simulation of the 40 times or full-scale scrubber physical envelope at E/STS and physical requirements dictated by thermal and hydraulic performance parameters. The former consideration constrains to some extent the ranges of length and diameters which can be employed since the E/STS scrubber must ultimately be contained within a fixed piece of real estate. The latter consideration is basically threefold. The duct must be large enough to supply cooling and scrubbing water at the relatively high rate of 350 GPM. It must be long enough to provide adequate impingement or other devices to separate the water from the gas stream. It must have length to diameter ratio based on the internal scrubber arrangement and gas and

water flow rates to operate efficiently at a low pressure drop. It appears that, with all of these considerations in mind, a duct envelope of from 14 to 18 inches in diameter and approximately 6 to 10 feet long will be required. About ten 3/4 inch diameter nozzles will be used to spray scrubbing water into the gas stream. These nozzles will operate at about 100 psi pressure drop at the maximum flow rates.

Perhaps the most difficult mechanical hydraulic problem involving the design of the scrubber is the method of draining the 350 GPM of water from the unit back into the catch basin or tank. Since the model scrubber will operate at approximately atmospheric pressure, there will be no pressure driving force to force the liquid out of the vessel. A static head of fluid of, perhaps, 3 to 4 feet will be available between the tank and the scrubber. Calculation of the fluid velocity which can be expected from such a static head indicate that the equivalent of a 3 inch outlet pipe will accommodate the 350 GPM flow. To provide a gas seal or trap inside the scrubber and to provide a full pipe flow in the drain, a weir arrangement will be employed in the aft end of the scrubber. It may also be necessary to operate the unit at a slight downward slope of several degrees to provide effective drainage.

8. Facility Separator

a. General

The model scrubbers which will be evaluated will be developmental in nature. As such, little will be known about their actual operating efficiencies. In some cases, before optimum operating parameters are established, low efficiencies can be expected. It is, therefore, highly probable that some radioactive matter from the test samples could escape entrainment in the scrubber model and pass through the flare stack into the atmosphere.

To prevent the escape of active matter into the air, an "absolute" separator will be installed in the exhaust line of the system downstream of the model scrubber. This permanent facility separator will perform two functions. It will remove all residual particulate matter and soluble gases from the gas stream both by scrubbing and by filtration and it will further reduce the temperature of the exhaust stream. In order to accomplish this "absolute"

separation, a commercial scrubber will be attached to the outlet of the model scrubber and a bank of two AEC-approved absolute filters will be installed in the exhaust of the commercial scrubber.

Table II shows the practical operating limits for the facility scrubber in terms of water rates and outlet temperatures of the gas and liquid streams (assumed to be in equilibrium). Since the proposed test plan specifies that the influence of model scrubber exit temperature (a primary parameter for scaling up to the E/STS scrubber) will be investigated over the range of 120°F to 160°F, the facility scrubber performance is based on these limits. Cases I and II represent operation at these temperature limits on the inlet of the facility scrubber with a lower temperature (100°F or "near ambient") on the outlet to reduce vapor losses. Although only 0.6 GPM are lost to vapor, maintaining this low loss rate requires scrubber rates of 250 to 430 GPM. These high water rates would be impractical for most commercial units which are designed for water rates on the order of 20 GPM. A high pressure drop through the scrubber would also place a high back pressure on the model scrubber. In addition, a large pump and water supply would be required for the facility scrubber supply.

Case III splits the heat load between the model and facility scrubber by allowing a 120°F exhaust temperature at a vapor loss rate of 1.2 GPM, although the vapor loss is double the original value, a water rate of 180 GPM is still required on the facility scrubber.

The final cases, IV and V, are based on a pre-selected scrubber water rate of 20 GPM which is adequate for most commercial scrubbers. There is no attempt to add substantially to the cooling of the gases with the facility scrubber, only to wash them. This results in a pressure drop for the facility scrubber which is on the order of 10 to 20 inches of water and a relatively small water loop is required for the scrubber. This advantage is gained by a corresponding rise in vapor losses in the exhaust of 3.3 GPM for the 160°F tests and 1.1 GPM for the 120°F tests. Although the 3.3 GPM is five times higher than the value for

TABLE II
FACILITY SCRUBBER PERFORMANCE

Mode of Operation	Facility* Scrubber Inlet Gas Temperature °F	Outlet Gas Temperature °F	Model Scrubber Water Rate gpm	Facility Scrubber Water Rate gpm	Water Vapor** Lost to Stack gpm
I	160	100	140	430	0.6
II	120	100	320	250	0.6
III	160	120	140	180	1.2
IV	160	153	140	20+	3.3
V	120	117	320	20+	1.1

* Model Scrubber Outlet Temperature

** Make-Up Water Required

+ Average Value for Commercial Scrubbers

Case I, the absolute level is still within reasonable bounds. This make-up water requirement can easily be met. However, it will be necessary to employ exhaust filters which will not be impaired by condensation of some of this water vapor.

b. Commercial Scrubbers

There are several types of commercial scrubbers which can be used and each will be evaluated from an operational and economical standpoint before procurement is initiated. These scrubbers can be classified in one or more of the following generic types:

- (1) Packed Beds
- (2) Wet Cyclones
- (3) Venturis
- (4) Turbine Vanes

The packed bed scrubbers are normally vertical, cylindrical-shelled vessels packed with ceramic or metal pieces with large area to volume ratios. These pieces are in the form of spheres, rings, or saddles to provide maximum contact between gas and liquid and between particulates and liquid. They clean dust and vapor laden gases by a water stream that descends by gravity from the top of the tower from a closed water loop. Entrainment devices near the top of the scrubber separate the water droplets from the exhaust gases.

A packed bed scrubber to perform under the 1/40 scale conditions (2000 SCFM maximum gas flow) would have a diameter of about three feet and a height of 10 to 12 feet. It could be made from stainless steel or from carbon steel lined with a corrosion resistant plastic or glass. The packing would likely be ceramic rings or saddles. Operating at water flow rates of about 20 to 25 GPM and a pressure drop of about five inches of water, the bed could provide removal efficiencies as shown on Figure 8.

Wet cyclone scrubbers are centrifugal devices which rely on both scrubbing action and centrifugal force to separate particles and heavier gas molecules from a gas stream. Gases enter the scrubber tangentially on the periphery of the cylinder where they are mixed with a high velocity water spray also directed tangentially. As the gas-water mixture swirls

FIGURE 8
TYPICAL PERFORMANCE CURVES FOR COMMERCIAL SCRUBBERS

around the outside of the scrubber, particles are forced outward toward the walls and soluble gases are dissolved in the water. The water flows in a helical path by gravity to the bottom of the cone-cylinder body of the scrubber and the gases move upward and toward the center where they are exhausted.

A wet cyclone scrubber for the model wet duct facility could operate at efficiencies similar to those in Figure 8 at a water rate of 20 GPM and a pressure drop of 10 to 20 inches of water. This configuration offers a size advantage in that an envelope of only 3 feet by 5 feet is required. It is also simple to install and maintain as well as to decontaminate.

Venturi scrubbers employ a parallel bank of venturis to provide highly efficient gas-solid-liquid contacting. Water is sprayed directly into the throat of the venturis by individual nozzles which are carefully positioned to provide maximum impact on the venturi walls. The impaction breaks up large droplets and as the gas-liquid stream is accelerated through the throat, these small droplets collect particles and soluble gases. Impaction baffles downstream from the divergent section of the venturi collect the water and entrained solids while the gases pass through to the exhaust. Although the venturi configuration provides highly efficient gas scrubbing, the trade-off in this case is in somewhat larger equipment sizes.

Turbine vane scrubbers are similar in principal to wet cyclones in that centrifugal forces are employed to affect the separation. In this case, however, the force is obtained by vanes and conical baffles along the axis of the cylindrical shell. These vanes can be rotated aerodynamically by the gas liquid stream or by external electrical drives. Water is injected near the vanes and impacts with the gas on the blades. The rotating blades then force the water and solids against the walls while the gases continue upward through the shell. In some designs, special ducts and blowers are used to recycle the gas through the system. As in the other commercial designs, a closed water loop can be used.

Vane scrubbers can operate at the collection efficiencies shown in Figure 8 with water requirements of 5 to 10 GPM and a low pressure drop of 10 inches of water at 2000 SCFM. A scrubber of this type would be about three feet in diameter and 8 to 12 feet high.

Any of these commercial scrubbers would fill the needs of the facility separator specifications. The optimum design will be based on the characteristics discussed above, on space limitations, certified efficiencies, and economics.

c. Absolute Filters

The wet duct facility is located within the WANL plant which, in turn, is in an area of moderate population density. It is therefore a requirement that strict control be maintained over stack effluents, particularly toxic or radioactive air pollutants. The facility scrubber can be designed to carry out the desired removal of contaminants; however, a secondary protection of a more absolute nature is required in the event of failure of the scrubber. This could occur in the event of a power failure, water stoppage, or sudden overload of the scrubber by an off-design release of particulate matter or toxic gases.

A bank of "absolute" filters will be installed in the effluent gas stream from the facility scrubber to provide this protection. The term "absolute" filter has come into popular usage as a result of AEC requirements for ultra high efficiency separation of sub-micron particles. These filters are now certified to remove 99.97 per cent of all particles 0.3 microns and above in diameter. As dust builds up on the surface of the filter this efficiency increases to over 99.99 per cent. The certification is based on the successful passing of a DOP (dioctyl phthalate) aerosol test per MIL-STD-282 dated 28 May 1956.

The filters are made in a honeycomb form having a high surface area. The honeycomb material is a fire resistant glass fibre. The mounting frames are fire resistant plywood or metal. The entire assembly is treated with water-proofing chemicals to permit operation in high humidity air. Condensation of water on the front surface does not damage the filter or impair the filtration.

Two of these 24 inch by 24 inch by 12 inch filters in parallel will provide rated particle separation efficiencies at 2000 SCFM gas flow and 0.9 inches of water. These filters can be used until the dust build-up on the surfaces is 14 pounds (for 2 filters) at which point the pressure drop is 2 inches of water. The weight loss from each irradiated sample plus the weight loss from the gas generator elements is expected to be substantially less than 0.5 pound per test. It is expected that a major portion of this amount will be collected in the model and facility scrubbers. Therefore, the filters should have a lifetime in excess of a year based on the number of tests proposed. They would be changed once a year, at any rate, under normal maintenance practices.

A light-weight metal housing for the filters would be inserted in the exhaust duct. This housing would have a pass-through door arrangement so that filters could be removed "semi-remotely" (at a distance of 3 to 5 feet) and placed in bags for disposal.

9. Water Systems

One of the most demanding of the facilities requirements is the water systems which will be employed in cooling and scrubbing the exhaust gases from the gas generator. Water will be employed to accomplish the following functions:

- a. Wet duct water injection to cool the exhaust gases from 4500°R to 1000°R.
- b. Model scrubber injection to further cool the gases to outlet temperatures of 120°F to 160°F and to wash solid particles and soluble gases from the exhaust gases.
- c. Facilities scrubber injection to remove additional solids and gases from the stream.
- d. Cooling water for the gas generator furnace, electrodes, jacketed ducts, and for the heat exchanger in the model scrubber loop, if required.

The first two functions will be accomplished in the primary water loop, the third in the secondary water loop, and the fourth in the coolant loop. These water supplies will be discussed below.

a. Primary Water Loop

This loop must supply, at maximum service, about 13 GPM at the wet duct inlet to provide initial cooling of the gases of 1000°R. It must also supply between 140 GPM and 320 GPM to the model scrubber depending on the desired outlet temperature. In both cases the delivery pressure is established by the pressure drop through the nozzles since the duct and scrubber pressures are essentially atmospheric.

The nozzles in the scrubber will operate at about 100 psi pressure drop maximum. A pump to supply this water and the injector water would operate at 22 horsepower and would have a 2-1/2 inch delivery size.

Primary control of flow split from the pump to the scrubber and wet duct would be accomplished with diaphragm-operated control valves in the supply lines as shown in Figure 9. These valves would be controlled by pneumatically operated flow controllers which receive process signals from transmitters measuring orifice differential pressure and fluid temperature.

The vapor losses from the primary loop would be made up automatically from the city water supply. Each line from the city water supply would have a check valve to prevent back-flow of contaminated water. The inlet valve would operate electrically on command from a liquid level controller which would sense the level of water in the tank.

An electrically-operated valve in the return line between the scrubber and the catch tank would provide a resistance to the return flow of water from the scrubber. This valve, also operated by a liquid level controller, would assure a constant liquid head in scrubber which would, in turn, prevent hydrogen from entering the catch tank. This function may also be accomplished by a barometric leg in the catch tank if the design is shown to be feasible.

Although additional analysis of the sampling method may dictate otherwise, it is anticipated that a filter unit will be employed in the return line of the scrubber to collect

large particles of fuel and fission products. This will facilitate quantitative sample analysis as well as to prevent build-up of contaminated particles in the water system. The use of the filter may not be advisable from the standpoint of increased flow impedance in the return line. The final system design will take these considerations into account.

The sizing of the storage tank will be based on the mode of primary loop operation. Basically two methods can be employed:

- (1) Closed loop recirculation (Figure 9).
- (2) One pass operation (Figure 10).

The closed loop operation would require a collection tank of about 500 gallons capacity. However, a heat exchanger would be required to remove up to 2400 BTU/sec of heat from the water in order to maintain the injector water at about 70°F. If this temperature is allowed to increase, a greater flow rate is required to maintain adequate cooling in the wet duct and scrubber. As will be seen later, the heat exchanger design can be one of the most difficult problems in the system design and a detailed economic and design analysis will be required before a firm decision on the mode of primary loop operation can be made.

The second mode of operation is a one pass method. Here, the water from a reservoir, probably in the cooling water loop, would be pumped through the scrubber and wet duct injectors and collected in a tank. For a nominal 15 minute test duration at a maximum water flow of 350 GPM, a 7000 gallon tank would be required. Automatic shut-down switches would be installed to terminate the test in the event that the tank filled before a normal test was completed.

The larger tank would be more costly than a small tank used in the recirculating system and sample analysis would be less accurate because of larger volumes (smaller sample concentrations). However, the one-pass operation offers advantages: First, no heat exchanger would be required to cool the primary loop water and, second, there would be no build-up of soluble contaminants in the scrubber inlet water as in the case of the

611659-1B

FIGURE 9
 WATER SYSTEMS SCHEMATIC (RECIRCULATION MODE)

FIGURE 10
WATER SYSTEMS SCHEMATIC (ONE-PASS MODE)

recirculating system. The latter advantage is substantial when it is noted that scrubber efficiency in dissolving soluble contaminants is impaired as their concentration in the water increases.

An additional problem with the one-pass system is the disposal of the 5000 gallons of water which would be contaminated during each test. This can be accomplished by evaporating the water in the Westinghouse Atomic Power Division evaporation facility at Waltz Mill, Pennsylvania. A tank truck is available to ship the water between Large, Pennsylvania and Waltz Mill. However, shipping over state or interstate routes would have to be approved by AEC and state authorities. It is possible that evaporation can be accomplished at the WANL site using a proposed evaporator which should be available at the time of these experiments.

Both of these methods of operation are feasible from the standpoints of economics, sample analysis, equipment design, and test operation. The selection of the better mode will be made in the design phase of the program after careful study of all these factors.

b. Secondary Water Loop

It was pointed out above that the facility scrubber would not be employed for further large-scale cooling of the exhaust gases from the model scrubber. Instead, the facility scrubber will be used as an efficient separator. This specification results in a substantial savings in the secondary water loop requirements. A flow rate of about 20 GPM is required. This can easily be maintained by a small pump operating at less than 1/2 H. P. A collection tank of about 200 gallons capacity would suffice. This recirculating tank can be included as part of the scrubber on most commercial units by adding a section on the bottom of the scrubber body.

Of course, even at the low flow rate of 20 GPM, some cooling of the exhaust gases occurs. Here again, two modes of operation can be employed. In the first method, no heat is removed from the secondary loop water and the temperature is permitted to rise to the value of the exit gases from the model scrubber. Referring again to Table II, the vapor loss from the system would then reach a maximum value of 3.3 GPM at 160°F exhaust temperature.

If the secondary loop water were maintained at 70°F as in the second method, the outlet temperature of the gases could be reduced to 144°F and vapor losses would be correspondingly reduced to 2.4 GPM at the most severe operating conditions. This reduction in temperature would require the removal of 205 BTU/sec from the secondary loop water. It does not appear economical to attempt to reduce these water losses by cooling this loop since additional heat exchanger equipment would be required.

The same type of flow and level controls would be used on the secondary loop as on the primary loop. These are shown on Figures 9 and 10. Make up water would again be supplied automatically to the recirculation tank.

c. Coolant Loop

The existing coolant loop at WANL will be used for cooling all furnace parts. This loop consists of a 15,000 gallon pond, recirculation piping, and a 500 GPM pump capable of operation at 200 psig. The water is cooled evaporatively when it is sprayed back into the pond from the return lines.

Under mode 2 (one pass) of operating the primary water loop, the pond would also supply the 5000 gallons of scrubber water required for a test. Under mode 1 (recirculation) of operation of the primary water loop, the pond would be used as a coolant supply for a tube and shell heat exchanger to cool the primary loop water.

There are several methods by which the heat can be removed from the primary loop. Only two appear feasible at this time. The first method, outlined above, involves a water-to-water heat exchanger. The scrubber effluent water at 120°F to 160°F would be cooled on the tube side of the exchanger by pool water on the shell side. The problems with this method are the low temperature difference between the hot water (120°F to 160°F) and the coolant (70°F) and the low temperature rise permitted in the coolant. These restrictions result in a relatively large size exchanger operated at high coolant flow rates. Some increase in the heat transfer can be accomplished by using ice water in the pond. This would be possible for short duration tests.

The second method attempts to solve the problem of low temperature driving force by using liquid nitrogen on the shell side of the exchanger. The temperature difference between the streams are then on the order of 400°F and, in addition, the heat transfer coefficient from forced convection boiling heat transfer of the nitrogen should be adequate. A somewhat smaller exchanger could be employed. The disadvantage of this method is the probability that icing will occur on the tube side in the low velocity region near the tube walls. This icing can be reduced to some extent by spoilers on the inside surfaces of the tubes to mix the water inside the tubes and increase turbulence near the walls.

B. SYSTEM PERFORMANCE

1. Sample Corrosion

The object of the proposed experiments is to determine the efficiency and operating characteristics of a scrubber for the removal of radioactive fission products from a hydrogen stream simulating the nozzle effluent of the NERVA test reactors. The plan is to provide irradiated, fueled graphite test pieces to be mounted downstream of a single cluster gas heater. The gas stream should have concentration of fission products as well as particulate matters that are consistent with reactor test conditions. The reactor fission product concentrations can be simulated by proper choice of the length of sample irradiation time. The particulate matter concentration must be simulated by designing a proper length for the test sample.

In order to provide data for a conservative scrubber design, it is important to study the worst condition in the reactor. This corresponds to the rate of weight loss near the end of life. It has been found that NRX reactor corrosion weight loss approximates an exponential function of time.² It is obvious that the rate of weight loss increases with time. At 30 minutes, the average rate of weight loss per element is 3.38 gm/min. Future test reactors are expected to run at considerably longer times with no greater total weight loss per element. If it is assumed that Figure 11 gives the worst rate of corrosion expected, then 3.38 gm/min would represent the upper limit. The total hydrogen flowrate per element is approximately 2.8 lb/min. On the basis of this flowrate, the corrosion weight loss per pound of

FIGURE 11

AVERAGE CORROSION WEIGHT LOSS RATE FOR FUEL ELEMENTS

hydrogen is 1.21 gm/lb-H₂. The model tests will utilize a hydrogen flowrate of 0.15 lb/sec or 9 lb/min. For this flowrate, the rate of test sample weight loss required is 10.9 gm/min. It is assumed that by reproducing the total weight loss per unit weight of hydrogen, the particulate concentrations can be reproduced.

a. Uncoated Samples

It was recognized that the high corrosion rates indicated above can only be attained with uncoated graphite materials. It is therefore intended to study both coated and uncoated test specimens with the same configuration as the support blocks. For the uncoated samples, the length of the test samples required to give the required rate of weight loss can be calculated by techniques reported in Reference 3. It can be shown that at the relatively high temperature (4500°R) and high flowrate (0.15 lb/sec) considered, the rate of surface regression changes very little with the length of the test sample. Consequently, for a pressure of 800 psia, a surface regression of 7.4 mils/min can be assumed. On the basis of a single fuel cluster configuration of six elements, the rate of weight loss with an average surface regression of 7.4 mils/min is given by the equation

$$\frac{dw}{dt} = 8.2L \text{ gm/min}$$

where L is the length of the sample in inches. The sample sizes corresponding to the average rate of weight loss for a typical reactor test at 30 minutes is 1.3 inches. For such a small sample, the irradiation time required to produce the desired fission product concentrations may be relatively long. Possible alternatives are to reduce the pressure or to introduce acetylene into the system, thereby depressing the corrosion rate so that a longer test piece can be used. An additional advantage in these alternatives is that the rate of surface regression will be reduced, permitting a longer test time. This is discussed in the next section.

b. Test Time Limitations

It is evident that having fixed the flowrate, temperature, and pressure, the rate of surface regression of uncoated samples would be determined. For a pressure of 560

psia, the rate of surface regression is estimated at 5.2 mils/min. If the pressure were 800 psia, the surface regression would be 7.4 mils/min. Now the distance between coolant channels is roughly 70 mils. It can be readily seen that at these high corrosion rates, the maximum test time possible is on the order of 4 to 7 minutes, i. e., if the tests are carried out to complete sample destruction. In practice, only test times considerably shorter than these are practical. A problem with a short test time is that the transient start-up period, required to bring the heater up to operating temperature, may be too long and overshadow the actual test time. However, this problem can be eliminated by starting up with helium and then switching to hydrogen.

In order to lengthen the test time, the rate of surface regression may be reduced by reducing the pressure or by the introduction of acetylene into the system. Acetylene may be introduced by metering the gas into the system or by the use of sacrificial graphite material (such as graphite felt) upstream of the sample. However, in the latter method, accurate control of the acetylene concentration would be most difficult if not impossible.

Other possibilities are the use of test samples of specially designed shapes, and the use of coated samples. The latter is discussed in the following section.

c. Coated Samples

The corrosion weight loss of coated samples can be readily estimated from electrical furnace fuel element corrosion tests. It is generally accepted that in the furnace tests, the corrosion weight loss is approximately a linear function of time in the hot end. Since the test samples will be mounted downstream of the single cluster, furnace test data taken under conditions similar to those anticipated in the operation of the scrubber tests may be used to estimate weight losses. The results give a rate of weight loss of $0.03L$ gm/min, where L is the length of the test sample in inches. The total rate of weight loss for different sample lengths are given below.

<u>L, in.</u>	<u>Rate of Weight Loss, gm/min</u>
2	.06
4	.12
6	.18
8	.24

It is evident that at these low corrosion rates, the tests can only simulate the beginning of reactor life. One important consideration however, is the fact that with coated samples at a low corrosion rate, the particulate concentration in the hydrogen stream would be at a minimum. Hence tests with coated sample will study essentially the efficiency of the scrubber in removing gaseous radioactive fission products only. This configuration would simulate molecular and atomic effluents which were introduced into the gas stream by solid diffusion through the graphite matrix of the fuel elements. Since the diffusion mechanism may predictably account for about 50 per cent of the fission products in the NERVA effluent gases, the study of coated samples may be important to the full understanding of scrubber operation. At the other extreme, where uncoated samples are used, the concentration of particulate matters would be at a maximum, and the scrubber can be evaluated as to its efficiency in removing particulate matters.

2. Thermodynamic Behavior

a. The Wet Duct Section

The water required to cool the hydrogen so that the hydrogen-water vapor mixture temperature is reduced to some given temperature can be readily calculated from a heat balance. The results are presented in Figure 12 where the final mixture temperature is plotted versus the water-to-hydrogen weight ratio for various inlet hydrogen temperatures. The calculations were based on a water temperature of 70°F.

b. The Scrubber Section

In the wet duct, both the hydrogen and water vapor are superheated. However, in order to operation the scrubber, the mixture temperature must be reduced to well below the

FIGURE 12
EFFECT OF WET DUCT WATER SPRAY RATE ON THE MIXTURE TEMPERATURE

water boiling point. In this case, the hydrogen from the scrubber would be saturated with water vapor. The total water requirement for the wet duct and the scrubber can be calculated from an enthalpy balance as follows:

$$H_{H_2} + W_{H_2O} (H_{H_2O, L} - H'_{H_2O, L}) = H'_{H_2} + x (H'_{H_2O, v} - H'_{H_2O, L})$$

where

H_{H_2} = the hydrogen enthalpy at the inlet to the wet duct

W_{H_2O} = total water flowrate per lb of hydrogen

$H_{H_2O, L}$ = the enthalpy of water entering the wet duct and the scrubber (assumed to be at the same temperature)

x = lb of water entrained in a lb of hydrogen at the exit of the scrubber

The primes denote scrubber exit conditions. Calculated results for water rates at various operating conditions in the scrubber and for various hydrogen temperatures are shown in Figures 13 and 14.

The amount of water vapor in hydrogen, x , can be calculated according to Dalton's Law by the equation

$$x = \frac{M_{H_2O} P_{H_2O}}{M_{H_2} (P_T - P_{H_2O})}$$

where

P_T = total pressure

P_{H_2} = vapor pressure of hydrogen

M_{H_2} = molecular weight of hydrogen

M_{H_2O} = molecular weight of water

FIGURE 13
EFFECT OF SCRUBBER EXHAUST TEMPERATURE
ON TOTAL WATER REQUIREMENTS

FIGURE 14
EFFECT OF SCRUBBER EXHAUST TEMPERATURE
ON SCRUBBER WATER REQUIREMENTS

The water vapor loss in the scrubber was computed on the basis of 0.12 to 0.18 lb/sec of hydrogen flow and scrubber exhaust temperatures ranging from 100 to 180°F. These results are presented in Figure 15. It can be seen that the rate of water lost is a small fraction of the total water flowrate.

The water used in the scrubber may have to be recirculated in order to facilitate the collection, analysis, and disposal of the radioactive materials. Consequently, the water in the primary loop will have to be cooled. The cooling load will depend on the amount of water required for the scrubber section. If a temperature of 1000°F is specified for the wet duct exhaust temperature, then the cooling load can be readily calculated from the relationship

$$Q_C = W_{H_2} (W_s - x) (H'_{H_2O, L} - H_{H_2O, L})$$

where

- W_{H_2} = total hydrogen flowrate
- W_s = scrubber water flowrate, lb per lb of hydrogen
- x = water vapor in scrubber exit, lb/lb of hydrogen
- $H'_{H_2O, L}$ = enthalpy of liquid water at scrubber exit
- $H_{H_2O, L}$ = enthalpy of inlet water (at 70°F)

The calculated results plotted in Figure 16 show that this cooling load is relatively high, between 2000 and 2500 BTU/sec at the proposed operating conditions.

c. The Facility Separator Section

The water requirement for the facility separator can be calculated from an enthalpy balance similar to that for the scrubber. The results calculated for various facility separator inlet and exit temperatures are presented in Figure 17. The water requirements are based on 0.15 lb/sec hydrogen flow and are given in gallons per minute.

FIGURE 15
EFFECT OF SCRUBBER EXHAUST TEMPERATURE
ON WATER VAPOR LOSS IN THE SCRUBBER

FIGURE 16
EFFECT OF SCRUBBER EXHAUST TEMPERATURE
ON COOLING LOAD IN THE PRIMARY WATER LOOP

$$H_2 = 0.15 \text{ LB/SEC}$$

FIGURE 17
EFFECT OF FACILITY SEPARATOR
EXIT TEMPERATURE ON WATER REQUIREMENTS

The cooling load in the facility separator can be calculated from the expression:

$$Q_{FS} = W_{H_2} \left(W_{H_2O}'' + x - x' \right) \left(H_{H_2O, L}'' - H_{H_2O, L}' \right)$$

The results calculated for 0.15 lb/sec hydrogen are shown in Figure 18 for different inlet temperatures. It is obvious that reduction of the outlet temperature of the facility scrubber can only be affected by substantial cooling of the facility scrubber water. The removal of this 100 to 200 BTU/sec to reduce the temperature of the exit gases by 15 to 25 degrees does not appear advisable based on the relatively small decrease in the total vapor loss which can be accomplished.

3. Radiation Consideration

Since this project will involve the use of a radioactive sample source and fission product activity will be released, provision must be made to protect operating personnel and the public. This can readily be accomplished by incorporation of standard radiation shielding practices, utilization of AEC-approved absolute dust filters, treatment of liquid wastes covered under the Pennsylvania Commonwealth Industrial Waste Permits, and monitoring of test operations by professional health physics personnel.

The sample will be the source of greatest radiation hazard. It will produce an exposure rate of between 5 and 10 roentgens per hour at contact. This sample will be prepared, handled, and transported to the test cell in approved protective radiation shield equipment. The sample module retainer is also shielded and will be the last component installed into the test before operation. After the irradiated specimen is installed, the daily personnel working exposure will be less than the 100 milliroentgens weekly maximum permissible.

During the test, particles of graphite and UC_2 containing fission products will erode from the sample and be carried downstream into the scrubber and collection system. The bulk of the radioactive contaminants (~50%) is expected to be collected in the elbow

FIGURE 18
EFFECT OF FACILITY SEPARATOR EXIT TEMPERATURE
ON THE COOLING LOAD IN THE SECONDARY LOOP

discharge trap; and the balance (~50%) in the scrubber discharge water. In the event the scrubber model fails to effectively scrub, a facility separator will act as a backup to scrub the radioactive materials. Any particles that are entrained in the facility separator gas effluent will be collected by MSA absolute filters before the gas is released to the atmosphere.

During the test, the scrub water leaving the scrubber (350 gal/min) will flow through a free flowing filter or settling chamber, which will retain ~ 80% of its contaminants. The effluent will either be re-cycled back into the system (500 gallons total) or used as a once through operation (5000 gallons). It is expected that this water will have a contamination level between 1×10^{-3} and 1×10^{-6} microcuries/ml, exceeding the release limits to waters of the Commonwealth. Consequently, once all waste waters have been collected and sampled, the water will be passed through cuno type filters and discharged to the plant radioactive waste collection system for processing and disposal. The cuno filters and MSA filters will be closely monitored by Health Physics and properly shielded as required.

C. TEST PLAN

1. Irradiated Sample

a. Sample Preparation and Handling

Each sample will consist of an assembly of seven hexagonal fuel element segments, from 2 to 8 inches long, approximating a NERVA fuel element cluster. Each fuel element segment will be weighed on an analytical balance with a precision of 1 milligram, then loaded in a shipping container.

The samples will be irradiated at the Westinghouse Reactor Evaluation Center in a 10 kilowatt critical assembly for a time sufficient to product 1×10^{16} fissions. Following the irradiation the sample will be loaded in a shielded container for return shipment to WANL.

The shielded container is a hollow lead cylinder with internal dimensions 4 inches in diameter by 10 inches long. The wall thickness is 4 inches while the end plugs are 5 inches thick. This container will reduce 100 roentgen/hour sources to less approximately 10 milli roengen/hour doses at the external container wall.

At WANL the sample will be transferred to a shielded glove box. Component fuel element segments will be removed individually from the glove box and the number of fissions in each segment determined by monitoring in a high pressure ionization chamber. After determination of the activity level in each fuel element segment, the segment will be combined as a clustered assembly contained in an NbC coated graphite holder. The sample will then be transferred from the glove box to the corrosion furnace in a shielded container.

b. Sample Collection and Analysis

Following each test, the corrosion furnace will be disassembled and the sample will be returned to the shielded glove box. The individual fuel elements comprising the sample will be weighed and monitored for total activity.

Following disassembly of the corrosion furnace, quantitative washing of the duct and scrubber surface will be accomplished to wash bulk quantities of entrained materials into a catch tank. Smear samples of the internal exhaust duct and scrubber walls will be taken. Aliquot portions of the primary scrubber water effluent, the final wash water, and facility scrubber water will be taken, and in addition, the primary scrubber water will be filtered to collect particulate matter. Thus from each test there will be six sample areas:

- (1) Fuel sample (initial and final).
- (2) Smear sample.
- (3) Primary scrubbing water sample.
- (4) Facility scrubber water sample.
- (5) Particulate matter sample.
- (6) Equipment wash water.

All six of these samples will be subjected to a standard radiochemical analysis.

During reactor operation the prime radiological hazards are:

- (1) The inhalation of radioactive iodine released as submicron sized vapor.
- (2) The epidermal erythema resulting from a particle released by corrosion.

The radioactive iodines are released by a diffusion process via the precursors, tin, antimony, and tellurium. Consequently, radiochemical analysis will be made for the isotopes, Sn^{125} , Sb^{127} , Te^{132} , and I^{131} in order to determine the scrubber efficiency for these species.

Analysis of the fuel sample will be made in order to determine the amount of each species released. The amount of each species released together with the amounts of these species collected in the scrubber water along the duct and in the facility scrubber water will provide a measure of the removal efficiencies of these various stages.

Radiochemical analysis of the particulate matter will include the above radioactive species and will be extended to include analysis of gross gamma measurements to provide an activity balance. This gross gamma activity will be used to determine the efficiency of the scrubber for particulate matter.

Finally, radiochemical analysis of the smear samples for the above nuclides will permit the determination of an activity balance and provide a measure of expected contamination level of the E/STS 2, 3 duct and scrubber.

2. Flow Experiments

There are three basic goals of the experimental program herein proposed:

- a. The evaluation of various gas scrubbing concepts (as to their suitability for E/STS application) in terms of collection efficiency, design, and operation.
- b. The study of important design parameters for the concept chosen for E/STS application so that adequate scale-up can be accomplished.
- c. The collection of additional wet duct water injection and gas cooling data on the 1/40 scale for comparison with previous small scale tests.

The latter goal is an extension of previous work done at Aerojet General and Westinghouse to provide scale-up data for the design of the E/STS duct.

Contrary to previous studies, no attempt will be made to vary the flow, pressure, temperature, and power parameters. These will be held constant at values which simulate the full scale reactor tests. Therefore, wet duct injector and cooling performance will be based on one design point only.

The evaluation of the scrubber concepts will be accomplished at conditions which match actual E/STS operating parameters within the limitations of the 1/40 scale hardware and existing facilities, such as the power supply, furnaces, and water supply. These considerations result in the pre-selection of the following parameters:

- a. Chamber pressure and temperature of the hydrogen.
- b. Power input to the gas heater.
- c. Scrubber water inlet conditions.
- d. Wet duct operating conditions of water flow, gas flow, and temperature.
- e. Radioactive species and particle size distribution in the exhaust stream.

These parameters will be held constant throughout the test series.

There will be some difficulty in establishing radioactive species, but varying the irradiation time and otherwise tailoring the sample should provide a consistent set of fission products. The particle size distribution will not be controlled directly. Rather, the initial particle size of the UC_2 beads will match those in a reactor. It will be assumed that the results of particle generation by diffusion and erosion and the attrition of particles by impingement along the duct will produce a particle size distribution that simulates that for a typical full scale test. The assumption is not overly compromising since it is anticipated that the 1/40 scale performance will establish conservative design limits for the E/STS scrubber. That is to say, the particle size distribution and flow rates which will exist in the 1/40 model will tend to represent more severe conditions than in the E/STS duct.

There are several degrees of freedom remaining after the above parameters have been established. These apply to the configuration of the scrubber, the sample configuration,

and the condition of the scrubber outlet water. Once these are established, all other parameters are also effectively established as shown in Table III.

The scrubber configurations, which we will express as M , consists of length, diameter, spray injector and scrubbing concept, and collection or entrainment concept. The variables which represent the internal design of the scrubber will be considered as one parameter M . It is anticipated that the diameter will be fixed at about 18 inches. Three internal arrangements of scrubber injector and collection concepts will be evaluated as discussed in Section III.D.4 below. The length parameter, which determines residence time of the gas and water in the scrubber, will be evaluated as part of the M variable unless initial results indicate that a more detailed evaluation of length effect is required.

The scrubber outlet temperature T , is an important variable to investigate because of its effect on scrubber efficiency, vapor losses, and water requirements for both the 1/40 model and full scale E/STS scrubber. This parameter will, therefore, be studied over a temperature range from 120°F to 160°F. Above 160°F vapor losses increase rapidly and become excessive; below 120°F cooling water requirements become excessive.

Fixing scrubber configuration, outlet temperature, and reactor simulation parameters (gas flow rate, pressure, and temperature etc.) fixes the basic operating parameters of the gas and water systems. In most cases these are established by the hydraulics and thermodynamics of the system. These include water flow rates to the injector and scrubber, vapor losses from the scrubber, pressure drop through the scrubber, gas velocity through the scrubber, and scrubber inlet pressure. (The inlet pressure is also a function of the pressure drop in the facility separation system which is fixed by the commercial design.)

The remaining degrees of freedom are taken by consideration of the particulate and gaseous contaminants in the exhaust gases. These are established by specifying the configuration (C) and size (L) of the sample. Size here is represented by length, L , since the cross section of the sample is fixed as that of a regular fuel element cluster. Gas temperature

TABLE III
SUMMARY OF TEST OPERATING PARAMETERS

Parameter	Fixed Or Pre- determined	Independent Degrees Of Freedom	Established By Fixing Of Degrees Of Freedom	Valve, Range, Or Identification
Scrubber Configuration				
- Length		X		6 to 10 Ft.
- Diameter		X		14 to 18 In.
- Injector Concept		X		Venturi, Cone, Spray
- Collector Concept		X		Screen, Baffle, Gravity
Scrubber Outlet Temperature		X		120°F to 160°F
Scrubber Inlet Pressure			X	Approx. 800 psia
Scrubber Pressure Drop			X	1 to 5 psi
Scrubber Water Flow Rate			X	140 to 320 gpm
Scrubber Inlet Water Temperature	X			70°F
Scrubber Inlet Gas Temperature	X			1000°F
Vapor Loss to Stack			X	1.1 to 3.3 gpm
Chamber Pressure of Gas	X			800 psia
Chamber Temperature of Gas	X			4500°R
Hydrogen Flow Rate	X			0.15 lb/sec
Injector Water Flow Rate	X			13 gpm
Solids Concentration in Exhaust			X	-----
Gas Contaminant Concentration In Exhaust			X	-----
Particle Size Distribution In Exhaust	X			Unknown
Radioactive Species in Exhaust	X			UC ₂ , Sn ¹³¹ , Sb ¹³¹ , Te ¹³¹ , I ¹³¹ , Sr ²⁹ , Ba ¹⁴⁰ , Y ⁹¹ , Mo ⁹⁹
Sample Configuration (Type)		X		Coated and Uncoated
Sample Size (Length)		X		2 Inches to 8 Inches
Corrosion Rate of Sample			X	
Test Duration			X	5 to 15 Min.
Electrical Power Input	X			
Wet Duct Size	X			

and sample configuration define a corrosion rate which, in turn, establishes the concentration of gas and solid contaminants in the exhaust stream. Corrosion rate also fixes test duration since the regression of the surface of the sample takes place at a more or less fixed rate over a finite web thickness.

There are two irradiated sample configurations which will be employed: coated and uncoated. The uncoated samples of from 4 to 8 inches will provide a simulation of the "end of life" corrosion behavior of the fuel elements when gross corrosive and erosive material losses occur. The coated sample of 8 inches will simulate "on-design" operation of the fuel elements. In the latter case solid diffusion is the main mechanism contributing to material losses.

The experimental plan for the scrubber evaluation will consist of two parts. In the first, scrubber efficiency, η , will be measured for three scrubber configurations, M. Sample size and configuration and outlet temperature will be held constant. In the second, the most promising scrubber concept will be employed to generate scale-up data by evaluating its performance at various levels of outlet temperature, T; sample size, L; and sample configuration, C.

Efficiency, the response or yield for the experimental plan, is defined as:

$$\eta = \frac{\text{Total Activity of All Collected Material}}{\text{Total Activity Released From Sample}}$$

The denominator represents a sum of all gases dissolved in the water and all particles entrained in the duct, model scrubber, and collection tank. The material collected in the facility scrubber will not be included.

Table IV summarizes this discussion and defines the experimental plan. The use of plan 1 to screen the various scrubber concepts will make use of a constant sample size and configuration and a constant outlet temperature. Two replications of the experiment will be conducted for each scrubber configuration and collection efficiency will be measured. Using this measured efficiency to compare the three concepts assumes the following:

TABLE IV
EXPERIMENTAL DESIGNS

Plan 1: Comparison of Scrubber Concepts

	Scrubber Configuration		
	M_1	M_2	M_3
Replication 1	η_{11}	η_{12}	η_{13}
Replication 2	η_{21}	η_{22}	η_{23}

Constant: C = Uncoated
T = 140°F
L = 4 Inches

Plan 2: Evaluation of Scale-Up Parameters

		Outlet Temperature	
		T_1 120°F	T_2 160°F
C_1 Coated Sample	L_1 4 Inch Length	η_{111}	η_{112}
	L_2 8 Inch Length	η_{121}	η_{122}
C_2 Uncoated	L_1 4 Inch Length	η_{211}	η_{212}
	L_2 8 Inch Length	η_{221}	η_{222}

Constant: M (Most Promising Concept)

- a. No interaction between S and M.
- b. No interaction between L and M.
- c. T can be established by thermodynamics and no T x M interaction.

By no interaction between two variables we mean that the effect of one variable on η is the same at any level of the other variable. This assumption must be made in these screening tests to reduce the number of requisite experiments.

In the second plan, the assumption of no interactions is not made. In fact, one of the goals of the experiment is to measure these interactions between variables at different levels. This series of experiments will be conducted at two levels of sample size (4 inches and 8 inches) for two sample configurations (coated and uncoated) over two levels of outlet temperature (120°F and 160°F). The results will determine whether or not there is a linear effect of L and T on collection efficiency. A prohibitive number of experiments would be required for a determination of quadratic or cubic effects. In addition to these main effects, the statistical analysis of variance for the experimental plan will show whether there are interactions between variables (T x L, S x T).

There are secondary considerations which will be considered in the evaluation of these results. These are briefly:

- a. The influence of the presence of dissolved materials in the scrubber water especially in the event a recirculating system is employed.
- b. Influence of high transient concentrations of contaminants in the gas stream which place a high rate-short duration demand on the scrubber.
- c. Influence of massive sample erosion as a result of mechanical failure, over-temperature, or other off-design operation.

3. Scrubber Models

a. Design Considerations

The fission product activity released from the NERVA reactor operation is comprised of two physical forms:

(1) An atomic dispersion resulting from fission products which diffuse from the core. The state of agglomerates of these products may be solid, liquid, or gas depending on their identities and the pressure and temperature of their environment.

(2) Substantial particles of graphite and UC_2 containing fission products. These particles originate from corrosional attack of the core by hydrogen, and may vary in size from a few microns to several millimeters.

Studies of system performance and radiation hazards at NRDS dictate that ninety-nine per cent of these contaminants must be removed by scrubbing of the E/STS exhaust gases.¹¹

The design of the scrubber will draw on the large background of gas scrubbing techniques available in industry. The problem of particle removal from a flowing gas stream has been the subject of extensive research and development. Air-pollution control of the atmosphere, maintaining the atmosphere in industrial clean or white rooms, and industrial recovery of valuable products such as dusts from smelters, are common examples of where particle removal is being accomplished.

The following physical properties of the carrier air or gas should be reviewed before designing or selecting a system for removing impurities:⁴

Quantity or flow rate, preferably by weight.

Temperature: actual at inlet, and desired at outlet.

Pressure: at inlet, and allowable change.

Density

Viscosity.

The following properties of the contaminants should be considered before designing or selecting equipment for their removal:

(1) Physiologic effects.

(2) Flammability, explosibility.

(3) Water distribution: solid, liquid, and vapor phase.

- (4) Composition of solids, liquids, and gases.
- (5) Concentration of each constituent.
- (6) Particle size distribution.
- (7) Unusual shape characteristics of solid particles.
- (8) Density of solid or liquid particles.
- (9) Porosity of solid particles.
- (10) Condensation temperature, or dew point of vapors.
- (11) Sublimation temperature, or freezing point of solids or semisolids.
- (12) Diffusivity of gaseous or submicron constituents.
- (13) Solubility in water or other collecting liquids.
- (14) Volatility or vapor pressure.
- (15) Hygroscopic or hydrophobic tendency.
- (16) Adhesive or cohesive nature of particles.
- (17) Presence of magnetic particles.
- (18) Electrical characteristics.
- (19) Hardness, abrasiveness, erosiveness.
- (20) Corroding or etching potential.

These considerations will form the basis of the design of the scrubber concepts which are to be evaluated to the extent that these effects can be reliably predicted.

Engine installation requirements place limitations on what may be done with the scrubber due to cost and feasibility. Two of these limitations are: the scrubber must be horizontal, and the diameter must remain within reasonable bounds, meaning relatively high throughput velocities must be maintained. This limits the scrubber to a straight thru concept.

The scale of the models chosen for test at WANL are 1/40th of the full scale nuclear rocket engine. This choice is based on the 3.0 MW size of the electric power supply, that has the ability to heat the hydrogen to 4500°R while maintaining average throughput velocities within the fuel elements at 50% of reactor normal element flows in an NRX reactor.

No clearcut criteria exist for defining the exhaust products, so it has been assumed that particles to be removed will range from an atomic dispersion through several millimeters. The performance and effectiveness of the scrubber models for removing these particles will be a function of liquid water to gas ratio, water droplet size, the uniformity of distribution of the water, the effectiveness of mixing regions, the time for mixing and wetting to occur and the availability of impingement surfaces on which the scrubbing water may collect. In selecting the models chosen for evaluation, these factors have been considered, and the tests to be conducted will evaluate these factors.

Simulation of the full scale approach flow conditions will be achieved in the scaled scrubber models by providing a four barreled simulated steam ejector capable of discharging a gas flow at the same conditions of gaseous hydrogen-water ratios, velocity, pressure and temperature.

b. Scrubber Model Concepts

The three models chosen for evaluation are: (1) a venturi scrubber, (2) a spray scrubber, and (3) a spray-on cone scrubber. A flexible shell concept is planned to contain these configurations. The features and operation of each of these models is described below.

(1) Model 1 - Venturi Scrubber

In this model, shown in Figure 19, the contaminated gases will discharge from the four simulated ejectors into the scrubber plenum resulting in a velocity reduction. Entrance thermocouples will provide for gas temperature measurements. About one foot downstream there will be a multiple venturi section with water spray nozzles carefully positioned with respect to the venturi inlet. This positioning is critical relative to achieving a high efficiency of particle removal. In this concept, water is sprayed from a nozzle with a conical discharge providing the first scrubbing action just ahead of the venturi. This spray cone then impinges on the venturi-inlet curved surface and rebounds, creating a second spray cone inside

FIGURE 19
MODEL 1 - VENTURI SCRUBBER

611659-5B

the venturi that provides the second scrubbing action. High efficiency is achieved due to the uniform distribution of finely atomized water and the differential velocities created in the venturi between the gas with its entrained particles and the water sprays.

Several feet downstream of the venturi exit section is placed the impingement baffle section containing four baffles. The temperature of the gas stream at this point in the scrubber is planned to range between 120 and 160°F, and the operating pressure a few pounds above atmospheric so that the bulk of the water introduced at the wet elbow and in the scrubber will be liquid, and will be dropping out as the gases enter the baffle section. The water droplets will be carrying the radioactive particles to be removed, and as they impinge on the baffles, will drop to the bottom of the duct and will be drained off as a liquid into the water outlet manifold. A thermocouple will measure exit gas temperature so that the system may be operated within prescribed temperature limits.

(2) Model 2 - Spray Scrubber

This scrubber, shown in Figure 20, is the least complex of the three proposed models. It will be the least costly to build, and will have the lowest pressure drop and therefore is the most desirable configuration for the full scale engine facility. However, it may not provide the required performance with regard to the percent removal of the radioactive wastes.

In this model, the contaminated gases entering the scrubber will be sprayed with water from two nozzle banks. The first four nozzles will index with the four discharging ejectors where the gas velocity will be high relative to the water sprays. About one foot further downstream, an additional 8 nozzles will spray the gases. This staged injection should result in a good water distribution throughout the gas stream, and will not result in excessive blockage in one plane, thereby keeping pressure losses at a minimum.

Two feet downstream of the second water injection plane will be the start of the impingement collectors consisting of half-round pipe installed vertically. They will be staggered axially so as to provide a minimum blockage in any one transverse plane,

611659-4B

FIGURE 20
MODEL 2 - SPRAY SCRUBBER

yet they will be overlapping each other, so that when viewed looking upstream in the duct they will appear to completely block the duct. This should result in a high collection efficiency of the water and contaminant particles, yet result in a minimum pressure drop of the flowing gas stream. As the water impinges on these pipe collectors, it will then flow downward to the bottom of the duct where the water outlets will drain it into a manifold. As shown in the figure, dams may be desirable in the bottom of the duct to help collect the water and drain it from the scrubber duct.

(3) Model 3 - Spray-On Cone Scrubber

The principle of operation of this scrubber is to provide a maximum opportunity for contact between the suspended matter in the gas and a surface wetted with the scrubbing water. This is accomplished by placing a number of cones facing into the following contaminated gas stream.

The details of this model are shown in Figure 21. The cones are arranged in three axial locations, each with its own water spray nozzle placed immediately upstream. By placing the cones in three planes, four in the first, one in the second, and four in the third, blockage to the flow of gases in any one plane is limited to 25% to keep the gas stream pressure losses down. When viewed looking upstream, the cones appear to very nearly block the duct. This fact combined with the water spraying over a large area due to impacting on the cones should result in a thorough wetting of all the particles to be removed, a prerequisite to high scrubber efficiency.

Two feet downstream of the second water injection plane will be placed the impingement baffle section identical to that used in Model 1. Here the water containing the contaminant particles will be removed from the scrubber.

c. Similarity Criteria

The results of the proposed experiments will be employed in three ways:

- (1) To compare different scrubber concepts.

FIGURE 21
MODEL 3 - SPRAY-ON CONE SCRUBBER

611659-3B

(2) To study operating characteristic parametrically for the best of the concepts.

(3) To provide scale-up design data for the E/STS scrubber.

The degree of similtude requirement for the scale model increases for each of the above functions in the order in which they are listed. Thus, to compare three different concepts one needs merely to provide identical conditions in the gas streams, water streams, and contaminant streams and to match those in the E/STS facility. It can then be assumed that the scrubber concept which has the highest efficiency relative to the other concepts under these conditions can be expected to perform best in the E/STS facility.

To study operating characteristics as in (2) above involves a somewhat greater concern for similarity with the E/STS duct in that the prediction of the absolute level of efficiency is desired. Thus, the interactions between operating characteristics such as water flow rate and temperature and scrubber dimensions (for example) are important.

The third function, scale-up, involves the most severe similarity requirements because it is then necessary to use the model data to design a scrubber 40 times larger.

In general, modeling for the purpose of scale-up involves the construction of a theoretical or empirical model which can be used to predict the behavior of a portion of the component or operation in question. This theoretical or empirical model is usually expressed in terms of a one or more dimensionless groups such as Reynolds Number, Froude Number, Weber Number, and others.⁵ These groups are then the basis for scale-up. For example, if Reynolds Number is taken as the similarity criteria for flow in ducts, then the results of a small scale duct experiment can be applied directly to the design of a large duct if the Reynolds Number is the same in each case.

Unfortunately, the modeling of scrubber concepts is an extremely complex task because the internal functions of the scrubber involve several separate and somewhat independent components each of which may have a profound influence on collection efficiency and other operating characteristics. These components or areas are:

- (1) The entrance plenum.
- (2) The nozzle sprays.
- (3) The impaction and/or inertial scrubbing devices.
- (4) The plenum following the inertial devices.
- (5) Impaction baffles or other collecting or entrainment devices.
- (6) Outlet Plenum

Establishing operating parameters and equipment dimensions in each of these areas is obviously important to the overall efficiency of the scrubber. Yet, each specific area has a different modeling criteria. Thus in the plenums where water is settling out of the gas stream by gravity effects, the Froude Number, which is a ratio of inertial to gravity forces, may be important. The Reynolds Number which compares inertial to friction forces may be the dominant criteria in venturis and other inertial scrubbing devices. Further, entrainment of liquid droplets containing contaminants from metal surfaces of the baffles or other impingement devices may be characterized by Weber Number, a ratio of inertial to surface tension forces.⁵

The design and final sizing of the model scrubber will be based on a consideration of these factors as well as the space demands and operational demands of the complete experimental system. In view of the complexity of the similarity analysis reviewed above, extensive studies will be made during the design and analysis phases of the program to establish effective similarity criteria for proper modeling and for adequate scale-up to the E/STS facility.

IV. REFERENCES

1. "Evaluation of Wet Versus Dry Systems and Supporting Studies for NERVA Exhaust and Altitude Simulation Systems," The Marquardt Corp. , January 1967.
2. "Joint WANL/LASL/Y-12 Fuel and Reactor Development Review," WANL-TME-1532, October 11-12, 1966, p. 1-90. (Confidential Restricted Data)
3. "Hydrogen Corrosion of Graphite Materials and Graphite Reactor Components," J. W. H. Chi, WANL-TME-1151, June 9, 1965, p. 51-54. (Confidential Restricted Data)
4. "Industrial Hygiene and Toxicology," 2nd ed. , Vol. 1, Patty, F. S. , Interscience Publishers, Inc. , New York, 1958, p. 229-283.
5. "Similitude in Engineering," Murphy, G. , The Ronald Press Co. , New York, 1950.