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SCALE MODEL TESTS OF A NUCLEAR ROCKET EXHAUST SCRUBBER*

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ABSTRACT

Measurements made during ground tests of Rover and Nerva nuclear rocket reactors, have shown that significant amounts of fission products are released from the fuel elements into the exhaust of the rocket and that these fission products can be carried considerable distances by atmospheric winds. An investigation was made at this Laboratory to determine the feasibility of reducing this fission product release to the atmosphere. A concept based upon a water scrubbing system was developed and shows promise in achieving this goal. A furnace was built to produce simulated nuclear rocket exhaust containing fission products at design conditions. The effluent from this furnace was run through a scale model scrubber. Several runs were made and the results indicate that about 80% of the fission product iodine and its precursors, as well as other fission products, can be removed from the exhaust-gas stream by this method.

INTRODUCTION

Nuclear reactors for rocket application, using solid core heat exchangers, have been undergoing development testing at the Nuclear Rocket Development Station, Jackass Flats, Nevada for approximately ten years. The first such reactor was "KIWI A" tested in July of 1959; since then 13 additional reactors have been tested. The most recent tests have been conducted at power levels greater than 1000 Mw and had durations ranging from 5 minutes to one hour. Following such tests, the reactor core contains an inventory of 10^{22} to 10^{23} fission products.

In these ground tests the hydrogen propellant from the nuclear rocket is directed upward and forms a large burning plume. The violent upward thrust of the plume entrains dust from the area surrounding the test pad and carries the exhaust to altitudes of several thousand feet at which point the upward motion ceases and a visible cloud forms which drifts horizontally and downward. Figure 1 shows the Phoebus 1B exhaust plume. Measurements of the radioactivity present in the exhaust, in the cloud, and in fallout reveal that significant quantities of the fission products find their way into the exhaust. The processes of thermal diffusion, as well as the erosion of the fuel elements in the reactor core, are the mechanism of release. Approx-

mately 1-5% of the total fission product inventory is released in this manner from a typical test. This "fallout" has produced local contamination of the test pad which required considerable decontamination efforts and because of off site considerations places rather restrictive requirements on the weather condition under which a test may be held. For past tests, the offsite fallout hazard was minimized by waiting for wind conditions which would carry the release over unpopulated country until sufficient dispersion had occurred to bring the levels below acceptable values.

In 1965, after the inception of the 5000 Mw reactor and engine program, the problem posed by the fission product release during a test was reconsidered. Both the test frequency and test duration appeared to increase the total fission product release to levels which would impede or even prohibit ground testing. As a result, efforts were made to determine whether there existed any method of reducing or eliminating the fission product release. Of course, reducing the source of the fission products through material choice and improved fuel element design is a continuing effort although it is unlikely that by this effort one can reduce the source to zero, and even at levels below those required for satisfactory engine operation there would still exist measurable and significant offsite fallout activity.

The possibility of collecting the effluent and thus preventing its release to the atmosphere was examined and it quickly became evident that the collection and handling of 10^3 standard cubic feet of hydrogen with a total energy $\sim 10^{12}$ BTU produced during a one hour test was not economically feasible.

The possibility of scrubbing by direct contact of the exhaust with water sprays was next considered. This technique had been used successfully in industrial scrubbing applications and also in the scrubbing of toxic compounds from the exhausts of chemical rocket and jet engine exhausts. From engineering and economic view points the system appeared feasible, the water storage and flow rates being well within the present capabilities.

The unknown chemical and physical nature of the fission products in the exhaust of a nuclear rocket made it difficult to analyze the scrubbing mechanism

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and to make any predictions about the process. It was therefore decided to perform scale model tests to answer the basic questions about the efficiency with which fission products could be scrubbed using a water spray system.

EXPERIMENTAL DESIGN

The water spray concept as applied to the nuclear system was based upon a two stage process. At the first stage sufficient water is injected into the hot hydrogen exhaust to produce a saturated steam-hydrogen mixture. The purpose of the first stage is to ensure a good mixing of water with the exhaust. At the second stage additional water is injected to mix with and condense a portion of the steam. It is in this stage that the scrubbing is expected to occur. Subsequent to this scrubbing the water drops containing the fission products are separated from the stream and the scrubbed exhaust is released to the atmosphere and burned.

Hot hydrogen gas at representative "design" conditions was produced in a resistance furnace, similar to those used for production testing of Rover fuel element. Figure 2 shows the main features of this furnace. The heating element consists of an unloaded, NbC coated "fuel element" which is electrically heated by passing through it current from a d-c generator. Hydrogen gas flows through the hot "fuel element" and is thus heated to the design temperature. The furnace is capable of power input to the gas of about a megawatt. At hydrogen flow rates of 5 lb/min this power produces gas exit temperatures of about 4000°R. The furnace is operated at 600-700 psig. The heated hydrogen upon exiting from the furnace is expanded through a small NbC coated graphite nozzle to produce a supersonic gas stream.

Fission products are introduced into the stream by placing into the furnace a pellet of fuel element material which has been previously irradiated in a thermal neutron flux. The pellet erodes in the hot hydrogen stream releasing fission products to produce a simulated nuclear rocket exhaust.

The supersonic gas stream enters the first station of the scrubber where water is injected radially inwards through a series of orifices. The saturated steam-hydrogen mixture produced in the first stage enters the second injection stage and additional scrubbing water is injected through spray nozzles. Following the scrubbing stages there is a water separation and collection stage. Separation of water drops containing the fission products is accomplished in two steps. The major portion of the bulk water is skimmed off by turning the stream through 90° as illustrated in Figure 2. The stream would in a full scale system then be taken to a flare stack and burned. For the purposes of the present experiment, however, it is necessary to do a complete inventory of the fission products including those which passed through the "scrubber". This is accomplished by collecting all the water from the 90° turn in stainless steel barrels and by absorption of the remaining fission products by passing the exhaust through a cold charcoal trap. To prevent blocking of the charcoal trap by freezing water in it, the effluent in this experiment is dried by injecting liquid nitrogen prior to the trap to remove all water vapor from the stream by condensation. This condensed vapor is also collected to complete the inventory.

EXPERIMENTAL RESULTS

The first runs were made using flow rates of 0.2 lb/min of hydrogen and water flow rates of 3 gpm. Exit gas temperatures greater than 3300°R were achieved.

The radioactive sample used to introduce fission products into the flowing hydrogen stream was a small cylinder of "KIWI A" type uranium-graphite which had been irradiated to produce about 5×10^{15} fissions in the sample. Because the sample was not clad, considerable corrosion took place during the 5-minute test. About 1/3 of the mass of sample was lost.

Following the test there were about 15 inches of water at Station 1 and less than 1 inch at Station 2. The solution at Station 2 was diluted to a volume equal to 1/3 of the volume of water at Station 1 and both solutions were acidified with HCl to stabilize the fission products. Samples of water were taken at both stations and a sample of charcoal was taken from the trap which follows Station 2. The solid materials at the bottoms of the barrels at both stations were collected on filters and were analysed along with the other samples.

Results of analyses using standard radiochemical procedures and gamma-ray spectroscopy can be summarized as follows. The efficiency for removal of activity from the gas stream ranges from a low of about 80% for iodine to a high of about 98% for yttrium. Tin, antimony, and iodine are all removed to about the same extent (80-84%); efficiencies measured for other elements are all greater than 90%. The preceding values refer to distribution of activity in solution at the two stations and in the trap; only activity found in solution at Station 1 is considered to have been scrubbed. Results are presented in Tables 1 and 2.

The activity in the solid material from Station 1 appears to represent material eroded from the sample by hot hydrogen. The ratio of activity on solids from the second Station to activity on solids from the first Station was .007 for tellurium, .002 for ruthenium, .002 for zirconium, .008 for barium, and 0.4 for iodine. The relatively large ratio for iodine is due more to a low value for iodine activity in Station 1 solids than to a high value at Station 2. The fission equivalent values for ^{132}Te and ^{131}I in Station 1 solids are 4×10^{14} and 1×10^{13} - both of which represent a small fraction of the activity in the solution (0.2 for ^{132}Te and .004 for ^{131}I). At any rate, inclusion of the activity found in the solids in the calculations of the scrubbing efficiencies will increase the apparent efficiency for everything except iodine. A decrease of the order of 1% will result for iodine.

As can be seen from Table 2, the fission product fractions collected at Station 1 represent a lower bound in scrubbing efficiency. The extent to which the fraction appearing at Station 2, in the LN₂ condensed stage, is contained in water drops which can be removed by more efficient separation is not known.

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TABLE 1. ANALYTICAL RESULTS FOR SOLUTIONS AND CHARCOAL TRAP, EQUIVALENT FISSIONS IN

Isotope Measured	Solution at Station 1	Solution at Station 2	Charcoal Trap
⁹⁹ Mo	2.9×10^{14}	1.4×10^{13}	$\leq 6 \times 10^{10}$
⁹¹ Y	2.9×10^{14}	5.0×10^{12}	1×10^{12}
¹²⁶ Sn	4.6×10^{15}	7.7×10^{14}	1.6×10^{14}
¹²⁷ Sb	3.9×10^{15}	8.0×10^{14}	7.2×10^{13}
¹³² Te	2.1×10^{15}	7.5×10^{13}	2.1×10^{13}
¹³¹ I	2.7×10^{15}	5.9×10^{14}	7.8×10^{13}
¹⁴⁰ Ba	1.2×10^{15}	9.6×10^{13}	2.2×10^{13}

TABLE 2. CALCULATED SCRUBBING EFFICIENCIES AND DISTRIBUTIONS OF ACTIVITY. (Values have been rounded off to nearest %.)

Element	Scrubbing Efficiency %	Fraction at Station 2 %	Fraction at Charcoal Trap %
Mo	> 99	< 1	~ 0
Y	98	2	~ 0
Sn	83	14	3
Sb	82	17	1
Te	96	3	1
I	80	18	2

FULL SCALE APPLICATION

Following the promising results of the first experiments, a study was undertaken to develop this concept for application to the Engine Test Stand No. 1 at NRDS. The engine operating parameters used in this study were 75,000 lbs thrust, exit temperature 5000°R, and hydrogen flow rate of 92 lb/sec. Because of the requirement for altitude simulation, the engine fires downward into a diffuser system and exhaust duct which uses steam ejectors to maintain altitude conditions during the start transients in a configuration shown in

Figure 3. The present diffuser design uses a spray cooled "wet elbow" to turn the gas stream exiting from the diffuser. The amount of water injected at this point produces a saturated hydrogen-steam mixture at a temperature of about 200°F and thus constitutes the first stage of a scrubber. This hydrogen-steam mixture exits from the duct proper at velocities of about 2700'/sec. Current studies indicate that subsequent water injection at a flow rate of about 25,000 gpm could be accomplished in a constant momentum diffuser section in which the water is injected through an annular manifold of spray nozzles. In the diffusion process the stream velocity is reduced to about 100'/sec in the course of accelerating the water drops.

Subsequent water removal from the full scale system has been the subject of a study⁽¹⁾ made by the Aerotec Division of Universal Oil Products, Greenwich, Connecticut. Water separation is accomplished in two steps. First a major portion of the water, (50-75%), is reduced by skimming vanes in a 90° turn. The second stage of water separation is based upon the use of high efficiency cyclone separators shown in Figure 4. These cyclones⁽²⁾ have been used in a variety of industrial applications to remove dust and liquids from process streams with efficiencies ranging between 80 to 95%. Figure 5 shows the manifold details for a bank of these separator tubes.

The requirement for altitude simulation for the engine test places an upper limit on the back-pressure to the steam generators of 2 psig. The study results indicated that 2000 ten inch tubes manifolded in two banks, as shown in Figure 6, would operate at 11" w.g. back-pressure with a peak back-pressure of 15" w.g. at full steam generator operation. Cost estimates of \$600,000 were made for this facility.

The present experimental work is continuing, upgraded by a factor of 10 to study and optimize water injection and the cyclone separation techniques. Figure 7 shows this arrangement schematically. This system will be operated at power inputs up to 1 megawatt and flow rates of 5 lb/min.

CONCLUSIONS

Experimental scale model tests have shown that fission products contained in a hot hydrogen gas stream representative of nuclear rocket exhaust gas can be scrubbed by a water spray and that 80-100% of the fission products of interest are thus removed. Feasibility studies indicate that full scale scrubbers based upon this concept are economically and technically feasible. Present work is continuing to determine the optimum quantities of water and injection and separation methods.

REFERENCES

1. Mechanical Collector Study for Nerva Exhaust Duct Application, Aerotec Division of Universal Oil Products, Greenwich, Connecticut, 2-2-68.
2. Cyclone Dust Collectors, American Petroleum Institute, 2-1-55.

FIGURE 1 - PHOEBUS 1B FULL POWER TEST
POWER: 1500MW HYDROGEN FLOW RATE: 105LB/SEC

FIGURE 2 - FIRST SCALE MODEL SCRUBBER SCHEMATIC

FIGURE 3 - NERVA ENGINE EXHAUST DUCT SYSTEM

FIGURE 4 - CYCLONE SEPARATOR TUBE DETAIL

DO NOT SCALE THIS DRAWING

SKETCH III

FIGURE 5 - CYCLONE SEPARATOR TUBE MANIFOLD

FIGURE 6 - FULL SCALE SEPARATOR CONFIGURATION

2ND MODEL SCRUBBER

OPERATING PARAMETER:

CH_4 FLOW - 2 lb/min

H_2O FLOW - 14 g/min

LN_2 FLOW - 120 lb/min

FURNACE POWER - 500 kW

FIGURE 7 - PRESENT SCALE MODEL SCRUBBER SCHEMATIC