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UPGRADING OF
NUCLEAR INSTRUMENTATION
ON 42" GASIFIER
AN EVALUATION REPORT

for
United States Department of Energy
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Prepared by

Victor V. Verbinski
Science Applications, Inc.
1200 Prospect Street
La Jolla, CA 92037

Frank Patricelli
Science Applications, Inc.
3 Choke Cherry Road
Rockville, MD 20850

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P.O. Box 2351, 1200 Prospect Street, La Jolla, California 92037

TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
1 INTRODUCTION	1
2 DATA FROM SITE VISIT	3
2.1 Gamma-Ray Sources	3
2.2 Gamma-Ray Field Mapping	4
2.3 Detector Responses	6
3 THE IONIZATION CHAMBER	12
3.1 Gamma Field Strength and Field Change Requirements	12
3.2 Reliability of the Ionization Chamber	12
3.3 Operation of the Ionization Chamber as a Densitometer	13
4 PROPOSED GAMMA-RAY SOURCE CONFIGURATION	15
4.1 Ra-226 Sources	15
4.2 Co-60 Sources	15
5 PROPOSED LEVEL-DENSITY GAUGE CONFIGURATION	16
5.1 Option 1A	16
5.2 Option 1B	16
5.3 Option 2A	16
5.4 Option 2B	17
6 SUMMARY AND CONCLUSIONS	18

1. INTRODUCTION

This report presents an evaluation of the present state and the future requirements of the nuclear instrumentation for the MERC 42-inch Coal Gasifier Plant (Producer) and is based on an evaluation of the data gathered during a site visit in the week of October 16, 1978, and earlier visits and data presented in the Request for Proposal (RFP) #EY-78-R-21-8218.

Data gathering during the site visit took advantage of a more stable and highly accurate radiation meter (Victoreen 440A) calibrated with a strong (100 millicurie Cs-137, calibration NBS traceable) gamma-ray source wherein both the high and low regions of the scale could be calibrated without severe $1/R^2$ gradients. The gamma-ray field strengths presented below are therefore more accurate and are felt to be free of error sometimes associated with gauge instability. This affects the conclusions as to minimum Co-60 source requirements for good level-gauge and densitometer performance.

Since the original RFP, a significant amount of work has been performed on the nuclear gauges by MERC personnel in upgrading the GM (Geiger Muller) tube level gauges. The electronics, for the most part, have been moved to the control room with analog outputs proportional to count rate, made available, as well as the trip-level (hi-low) adjustments. The hi-low level-indication readings are now on a convenient display panel. The trip-level settings can be conveniently adjusted in the control room; an upgrading feature that facilitates rapid and reliable calibration and/or troubleshooting. The stable temperature of the control room adds significantly to the stability of the electronics.

This system as it now stands is ahead of the state of the art in that the commercially available systems that have similar remote electronics capabilities all transmit the analog (variable pulse height) GM tube output rather than the digital output that is transmitted by the MERC system. Consequently, a separate highly shielded conduit made of 1/2-inch or 3/4-inch pipe must be run to the control room for each of the 8 level gauges (5 on the Producer and 3 on the coal and ash hoppers) to avoid electrical noise pickup. This is too cumbersome and too expensive to install compared to the flexible cable that is used with the MERC-modified system.

Unfortunately, the response times of some of the GM tube level gauges that operate in low gamma-ray field strengths are well above the desired 30 second response time called out for in the RFP. In addition, the GM tube outputs from the Producer vary by as much as 500% and tend to deteriorate rapidly compared to other alternative level gauge sensors (ionization chambers and NaI detectors). Their lower sensitivity precludes their use in providing density data and leads to costly long-range source requirements, maintenance requirements, and malfunctions during Producer runs.

To remain competitive, SAI will propose a GM tube system, as well as a highly-reliable ionization chamber option and a high-sensitivity fast-response NaI detector that also is highly reliable. The GM tube system will be sped up and made more reliable by utilizing selected GM tubes (and selected spares) and by raising the gamma-ray field strengths. This then will allow SAI (or MERC) to reduce the time constant of the GM tube circuit to the RFP-specified 30 seconds or less. However, replacement of some of the new Co-60 sources may be required after 3 1/2 years with this option to maintain the improved response time capability.

2. DATA FROM SITE VISIT

2.1 GAMMA-RAY SOURCES

Inspection of the three Co-60 gamma-ray source holders on the Producer and the three radium sources on the coal and ash hoppers showed the hasps for the padlocks to be in the proper place, such that the padlock keeps the shutter secured in the CLOSED position.

The source nameplate data, giving the initial Co-60 source strengths and the corresponding dates, are as follows:

Source at 2'5" (29")

Accuracy - Industrial Nucleonics Holder
LS 100 frame, Model LS-103, S6, CC1908
400 millicuries Co-60, 7/68

Source at 5'4" (64")

In-Val-Co (CE-In-Val-Co) Holder
Model B-20-100, Ser. #665
625 millicuries Co-60, April 3, 1969

Source at 7'1" (85")

Obmart, SHRD 2100 Series Holder
4000 millicuries Co-60, 5/75
Serial #1086

Communications with Gary Friggins of MERC have helped verify the nameplate data, including the source strength and date at which that source strength held true.

The source strengths at the time of this writing (11/78) are now 1030, 178 and 2526 millicuries, respectively, for the 29", 64" and 85" levels. The radium sources, having a 1600 year half life, will have essentially the same source

strengths as when purchased (0.75 mCi, 1.0 mCi and 1.5 mCi on the North and South Coal Hoppers and on the Ash Hopper, respectively).

2.2 GAMMA-RAY FIELD MAPPING

The gamma-ray field strengths shown in Table 1 were obtained with two separate measurements to avoid erroneous readings. They show, for example, that the 178 mCi middle source is next to useless and needs to be replaced with a 4000-5000 mCi source, the largest off-the-shelf Co-60 sources economically available.

The field strengths for the coal and ash hoppers are as follows:

S. Coal Hopper (0.75 mCi Ra-226): 1.1 mR/hr

N. Coal Hopper (1.00 mCi Ra-226): 1.7 mR/hr

Ash Hopper (1.5 mCi Ra-226): 2.5 mR/hr

It was noted that the output of the S. Coal Hopper GM tube was well below that of the N. Coal Hopper and the Ash Hopper, the latter being by far the higher.

The obvious repair of this condition simply involves a switch of the sources for the S. Coal Hopper and the Ash Hopper, with the source and detector on the Ash Hopper each being moved in a few inches for improved $1/R^2$ (geometric) effect. This is necessary, it should be noted, only if the GM tube level gauges are used. Some selection of GM tubes is also in order for the S. Coal Hopper. A switch to the ionization chamber type level gauge yields a factor of $\sim 2\frac{1}{2}$ in. sensitivity. In addition, a smaller percentage change in field strength is required for stable operation of the ionization chamber level gauge because it is inherently much more stable.

Table 1. Field Mapping (Gamma-Ray Dose Rates)
at 42-Inch Producer

LEVEL	ONE SOURCE OPEN FOR EACH READING ⁽¹⁾			ALL SOURCES OPEN (mR/hour)	GM ⁽²⁾ READINGS (Volts)	GM ⁽³⁾ SENSITIVITY (Reading/mR/hour)
	UPPER (mR/hour) 2.52 Ci Co ⁶⁰	MIDDLE (mR/hour) .15 Ci Co ⁶⁰	LOWER (mR/hour) 1.03 Ci Co ⁶⁰			
91"	.7	≤.1	≤.1	.75	5.92	7.89
86"	.7	≤.1	≤.1	.90	4.48	4.98
79"	.6	≤.1	≤.1	.60	1.59	2.65
67"	.45	≤.1	≤.1	.50	6.45	12.90
61"	.6	≤.1	.15	.90	3.80	4.22
					NaI Reading Counts/Sec	NaI Sensitivity Counts/mR
34"	.3	~.2	1.45	1.48	8667	1.73 x 10 ⁷
28"	.2	~.2	2.1	2.1	9667	1.66 x 10 ⁷

(1) All readings were taken with a 440A Victoreen radiation meter calibrated on 10/18/78 with 100 mCi Cs-137 source.

(2) GM readings taken from LED on control panel.

(3) GM sensitivity is GM reading/mR/hour (all sources open).

This is precisely the situation that calls for such an improvement because the percentage change of the field strength is marginally low at these locations where only about 1 ft. of coal or ash is interposed in the FULL condition and where the coal or ash may be non-compacted at times. In the past, it has always been very difficult to obtain a reliable trip-level (FULL to EMPTY change of state) setting at all three coal and ash hoppers because of the low sensitivity and corresponding high "jitter" (and response time) of these detectors.

2.3 DETECTOR RESPONSES

2.3.1 The NaI Density Gauges

2.3.1.1 Reliability

One of the two NaI detectors was found to be reading abnormally low. This was likely due to a defective connector or dirty pins in the cable connector, as determined by our getting the two to count the same high rate by means of simply switching the cable connectors at the rear of the dual channel density gauge electronics package (H.V. supply, amplifier, discriminator and count-rate meter).

These two densitometers are basically operational after more than 7 years of service (Gary Friggins, MERC, private communication). The proposed NaI replacements will not use a multiple-connector cable, but will use a much more reliable coaxial cable for both the signal and high voltage. Excellent noise shielding is realized with a coaxial cable. The high voltage is generated in the photomultiplier tube (PMT) base, utilizing an option of either a 5V or 12V supply transmitted through the single coaxial cable that also transmits the signal (via simple R-C coupling, decoupling and

isolation at both the PMT and electronics chassis). This design is now a reliable standard type of unit and is provided by several different manufacturers. It is modular so that field type troubleshooting can be done quickly by replacing either (1) NaI-PMT, (2) base, (3) amplifier-discriminator, or (4) count-rate meter with spares that will be provided.

2.3.1.2 Stability

It was noted that the PM tubes were operated near the edge, rather than at the center of, the plateau of the count-rate versus high voltage (H.V.) curve. The periodic maintenance and the corresponding maintenance manual provided as part of the proposed installation and service contract will ensure operation in the most stable configuration. Similar high stability operation, with the addition of a heater strip and button-sized solid-state temperature regulating switch (set for $105 \pm 3^{\circ}\text{F}$) provided stable operation, within $\pm 1\%$ count rate, over a period of one month in OUTDOOR use at the Colorado School of Mines Research Institute. The operating conditions varied from hot, sunny afternoons through a snow blizzard. A packaging similar to this (used in the SAI Coal Slurry Concentration Sensor designed and constructed for DoE, Pittsburgh Mining Operations) will be employed in the MERC Producer Density Gauges.

2.3.1.3 Counting Statistical Accuracy Versus Density Accuracy

Whether operating in current-measuring or pulse-counting mode, the accuracy of a detector (the "jitter" of the numerical output or of the densitometer needle) can be no better than the statistical limit of $(N)^{-\frac{1}{2}}$ where N is the

number of counts in the specified counting interval T . For the sake of standardization, let us take $T = 10$ seconds. (It is assumed that over the next seven years a time constant of the densitometer/level gauge system of 10 seconds or better will likely be needed).

The NaI count rate of ~ 9000 counts/sec (See Table 1) with the present 1030 mCi Co-60 source at the 29" level will be reduced by an attenuation factor A of about

$$A = (B + 1) e^{-\Sigma_t T} \quad (1)$$

where $B = \Sigma_t T$ is the buildup factor due to Co-60 gamma-rays down-scattered in energy, Σ_t is the macroscopic cross section for coal and T is the thickness. With $\Sigma_t = .063 \text{ cm}^2/\text{gm}$, $T = 42'' \times 2.54 \times 1.00 \text{ gm/cm}^2$, (the density of loose-packed Pittsburgh-seam bituminous coal is about 1 gm/cc) the attenuation factor becomes approximately 107 (the coal " $\frac{1}{2}$ -length" is thus about 6 $\frac{3}{4}$ ").

Thus, the NaI count rate is reduced to about 84 counts/sec (ignoring second order effects such as energy dependence of detector efficiency and iron shell of the Producer to scattered gamma-rays, which tend to cancel) or 840 counts/10 sec, giving a statistical accuracy of $(840)^{-\frac{1}{2}} \approx 3.4\%$.

Now, if the mean density of coal (due to a VOID, for example) is reduced by 5 pounds/cu ft., the counts will increase to $9000/A'$, where

$$A' = (\Sigma_t T + 1) e^{-\Sigma_t T((62.4-5)/62.4)} = 67.$$

Thus, the change of count rate (107/67) is nearly 60% about 17 times greater than the 3.4% statistical accuracy.

It is clear that even with the present 1030 mCi source, a 2" NaI detector will work well for the planned seven year service period. The new simple, modular circuits will provide the most trouble-free arrangement for this planned service period.

2.3.3 GEIGER MULLER (GM) TUBE LEVEL GAUGES

For the most reliable operation as level gauges, the GM tubes require gamma-ray fields of 2 to 5 mR/hr, container empty, and a field change of 75% to 100% between empty and full conditions. Operation in fields as low as 0.25 mR/hr has been claimed, but long time constants are usually involved and the GM tubes themselves change in characteristics with time. In 1977, when about seven of the newer and presumably more durable GM tubes were installed (all level gauge GM tubes are provided by 1 or 2 manufacturers, according to one of the level-gauge vendors) on the MERC Producer, several of them drifted in output by nearly a factor of two during the first 24 hour bake-in period. One got so low that it has to be discarded.

During the October site visit to MERC, it was observed that the analog outputs of the GM tubes used as level gauges on the Producer varied by ~350% (because of preselection wherein the more sensitive tubes are used in regions of lowest field strength). When normalizing GM tube output to unit field strength (see last column of Table 1), as much as 500% variations is observed between the five tubes.

For reliable operation on the Producer for a planned 7-year service period, the GM tube is not an adequately stable device. It produces an avalanche for each gamma-ray count, an avalanche that is quenched by a quenching gas up until the time that the quenching gas is destroyed by avalanches or, what is more probable, the quenching gas (the new long-life halogen quenchers) deteriorates by chemical interaction with the counter and with the trace gases that it gives off. After the quenching gas is no longer effective, self-induced avalanches (counts) can occur, the onset of which condition may be difficult

to ascertain, and eventually the counter goes out due to continuous non-quenched discharge.

One of the problems with using GM tubes as level gauges on the Producer is the desired field strength of mR/hr must be maintained over a period of seven years for highly reliable operation. Two new gamma-ray sources would be required at the 68" and 96" levels and may have to be replaced after about 3 1/2 years to keep the gamma-ray field strengths from falling below 2 mR/hr, a level of unsatisfactory operation for GM tubes. Twin tubes are used by some vendors, but probability of breakdown of a single tube is not improved by this tactic, and a breakdown in one of the two tubes can incapacitate a given level gauge.

In the case of the coal and ash hoppers, where the fields are 1-2 mR/hr, sources open, up to 0.45 mR/hr was observed in the source closed position (on the ash hopper) due to limited wall thickness of the source shield and/or shutter. Combining this leakage with the much smaller change in field strength in the hopper-full condition, as compared to the Producer and with fields as low as ~1 mR/hr (which low level necessitates a larger % change in "full" to "empty" conditions for reliable operation), results in marginal operation of the GM tubes on the coal and ash hoppers. Replacement with the ionization chamber type level gauge will solve these problems.

However, operation of the GM tubes over a period of 7 years is not out of the question. With the improvements achieved by MERC personnel in moving much of the electronics to the control room, the present configuration is now beyond the state of the art for commercially available gauges (See 3rd and 4th paragraphs of Introduction, Section 1, above). To remain cost competitive, SAI proposes to split Option 1 into Option 1A and Option 1B.

Option 1A involves the use of selected GM tubes at the five levels on the Producer and at the coal and ash hoppers, with the 96" and 68" sources on the Producer replaced with new 4000-5000 mCi Co-60 sources and the Ra-226 sources on the S. Coal Hopper and the Ash Hopper switched. The present upper source (96") on the Producer will be moved to the 40" level, where it will serve satisfactorily for 7 years. The NaI detectors will be replaced with the new modular type that uses a single cable. The NaI detector housing will be heat shielded and temperature controlled.

Option 1B is the same as 1A except that the GM tube level gauges are replaced by ionization chamber type level gauges that are more stable, more sensitive, have essentially infinite life, and have all the electronics located in the control room.

Option 2 is split into Option 2A and 2B, where 7 each NaI level-density gauges are utilized on the Producer and the three GM tube level gauges on the coal and ash hoppers (2A) are replaced by ionization chamber level gauges in Option 2B.

3. THE IONIZATION CHAMBER

3.1 GAMMA FIELD STRENGTH AND FIELD CHANGE REQUIREMENTS

This detector is about 4 inches in diameter, 7 inches long, and is filled to a much higher pressure than the GM tube: Since it operates in the linear "charge collection" region rather than the "avalanche" region, a much higher gas pressure can be used. For good drift-free stability, the DC current collected is "chopped" into an AC signal by means of a vibrating reed electrometer. Since no avalanche condition occurs, and no quenching gas is needed, the ionization chamber has essentially an infinite lifetime.

It can operate in gamma-ray fields as low as 0.1 mR/hr and requires only about a 20% change in gamma-ray field between hopper "full" and hopper "empty" conditions. Typical advertised GM tube level-gauge requirements are a minimum field strength of 0.5 mR/hr (although 0.25 mR/hr is claimed, when utilizing a long time constant of the order of one minute) and a required 75-100% change of field between "full" and "empty") for reliable operation. Thus, the ionization chamber will operate much more reliably at low gamma-ray field strengths, on the Producer, and will operate more reliably over small changes of radiation fields (~20% vs. 75-100%) such as on the coal and ash hoppers, where painfully long and careful calibration settings are now necessary (especially at the S. Coal Hopper, where the combination of small % change of gamma field and nominally low (empty condition) field strength exists.

3.2 RELIABILITY OF THE IONIZATION CHAMBER

In addition to the absence of avalanches and of a quenching gas to quench the avalanches (until the gas deteriorates), the ionization chamber has the added advantage of

having absolutely no electronics at the detector end. The signal and high voltage utilize a single cable which can be as long as 1000 ft. without deleterious effects due to cable leakage.

3.3 OPERATION OF THE IONIZATION CHAMBER AS A DENSITOMETER

Communications with the manufacturer indicate that the ionization chamber is about 15 times more efficient than the GM tube and about 1/15 as efficient as the 2-inch NaI detector.

For a 10 second time constant, the ionization chamber will detect about 56 counts/sec ($840/15$, based on the NaI estimated count rate) with an accuracy, as limited by the counting statistics, of $(56)^{-\frac{1}{2}} = 13\%$. This is much better than the expected count rate change of $\sim 60\%$ due to a change of mean coal density of 5 pounds/cubic ft. However, this count rate is somewhat below the instrument drift of the ionization chamber (and well below the instrument drift of the GM tube circuit).

With a gamma-ray field of ~ 2 mR/hr, Producer empty, and an attenuation of 107, a minimum field strength of about 0.02 mR/hr results. This is so low that a 60% change in this (for 5 lb/cubic ft. change of coal density) will be borderline in terms of circuit stability. In addition, it is not very practical to shield the sides and back of either the ionization chamber or the GM tube in their present configuration, whereas both shielding and pre-collimation (extension of the shield-opening forward of the detector) are very practical for the 2-inch NaI detector. In the "full" condition at the lower densitometer locations and the "empty" condition above, scattered radiation from above can result in serious interference with

the (2 mR/hr/107) $\approx$ 0.02 mR/hr gamma field expected from the lower source that irradiates the bottom two densitometers.

In conclusion, the ionization chamber will provide much better statistical accuracy than the GM tube for operation as a density gauge, but not nearly as good as the NaI detector. It can provide more useful density data than the analog output of the GM tube, for potential use at the 61"-91" levels, but cannot be guaranteed to meet the minimum density detection of $\pm$ 5 lbs/cubic ft. called out for in the RFP because of electronic stability limitations. For use as a density gauge, a side and back shield of 1/4" to 1/2" of lead will be necessary for cross talk (discussed above) and background reduction.

4. PROPOSED GAMMA-RAY SOURCE CONFIGURATION

4.1 Ra-226 SOURCES

Switching of the S: Coal Hopper and Ash Hopper sources is recommended with efforts to bring the source as close as practicable to the Ash Hopper chute, if GM tube level gauging is used (Option 1A or 2A).

4.2 Co-60 SOURCES

In Option 1A, two 5000 mCi sources will be installed at the 58" and 89" levels of the Producer, with each fanning out to cover all five level gauges (61" through 91" levels) so as to raise the field strengths to 3-5 mR/hr. This will compromise the level precision, to some extent, but will, on the other hand, circumvent rabble-arm shadowing if the trip levels are set so as to fire in the low GM output region (this will be called out in the maintenance and calibration schedule).

For all other options, one new 5000 mCi source will be located at the 86" level and the present top source (now 2526 mCi) lowered to the 64" level, as above. However, the 86" source will irradiate only the ionization chambers or NaI detectors at the 79", 86" and 91" levels and the 64" source will irradiate only the 61" and 67" ionization chambers or NaI detectors.

5. PROPOSED LEVEL-DENSITY GAUGE CONFIGURATION

5.1 OPTION 1A

Selected GM tubes and several selected spares will be obtained after "burn-in" of several days to one week of continual operation and will be used for the coal and ash hoppers as well as the 61", 67", 79", 86" and 91" levels on the Producer. The Ra-226 sources on the S. Coal Hopper and the Ash Hopper will be switched and moved closer to the chute for the Ash Hopper. The present MERC-improved electronics configuration will be used. Each GM tube on the Producer will view the upper two Co-60 sources, which will circumvent rabble-arm shadowing with proper setting of the trip levels. This will be at a cost of poorer definition of the coal level. Two new modular type NaI detectors (2"x2") will be located at the 28" and 34" levels.

5.2 OPTION 1B

This is the same as Option 1A, except that ionization chamber type level gauges will replace the GM tube gauges, and the 86" Co-60 sources (4000 mCi) will be more tightly collimated so as to obtain better coal-height resolution. Rabble-arm shadowing will be circumvented by activating amber lights for each of the 7 levels on the Producer. These will be operational at some future date when MERC installs (and calibrates by observing where shadowing occurs) rabble-arm position transducers on the rabble-arm shaft or some other equivalent location.

5.3 OPTION 2A

This option utilizes 7 NaI level-density gauges on the Producer, with the Co-60 source configuration as per Section 5.2 above (including rabble-arm shadowing circumvention

via amber indication lights to be activated later by MERC personnel). The three level gauges on the Producer are GM-tube-type level gauges. The Ra-226 sources on the S. Coal Hopper and Ash Hopper are switched as per Section 5.1. Both level-gauge (on-off) and densitometer (analog) type data will be available from the NaI detectors.

5.4 OPTION 2B

This is identical to Option 2A except that ionization chamber type level gauges replace the GM-tube type. The Ra-226 sources need not be switched on the S. Coal Hopper and the Ash Hopper.

6. SUMMARY AND CONCLUSIONS

At the risk of a complicated offering, four options have been presented for the sake of covering the range that extends from a lower priced option (1A) to a high performance option (2B). Option 2B is unqualifiedly recommended for providing the most complete Producer data and the fastest and most accurate response. These density and level data can be fully utilized when computerized control and the faster (future hydraulic) rabble arm action are introduced, which will greatly facilitate achieving the desired modes of Producer operation for long range studies of both the production and the off-gas treatment processes.

Option 2B is rated as the most reliable on the grounds that the largest number of crystals and photo-multiplier tubes are used: similar units have been basically operational for about seven years at MERC. The ionization chambers, having intrinsically infinite lifetime, have not been used at MERC. However, these are also expected to have a high overall reliability. They are utilized in Options 1B and 2B. Not only their lifetime, but their capability of operating with a lower gamma ray total field strength and with a lower change in field strength (as is required on the coal chutes and ash hoppers) make them far superior for operation as level gauges over a seven year service period. They are also much faster than GM tubes, which will reduce the probability that the level gauges (with ion chambers) will limit the control capabilities of the Producer.

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