CONCLUSIONS

A literature search on gas/liquid/solid fluidized systems has shown that a significant amount of information exists in the area of the hydrodynamics of fluidization, experimental techniques applicable to three-phase systems, and physical properties of solid/liquid systems.

In developing a mathematical model to describe the gas and liquid holdup in an H-Coal reactor, it has been found that information on liquid/solid and gas/liquid systems is of crucial importance. Although several correlations of liquid/solid systems were found, only the Richardson-Zaki correlation was tested with available literature data. Since this correlation does an excellent job in predicting the bed expansion of solid particles, testing of other correlations was deferred until more data on liquid/slurry systems are obtained in Amoco under the H-Coal fluid dynamics project.

The significance of gas/liquid systems in understanding the empirical or semi-empirical correlations of gas/liquid/solid systems was extensively reviewed. Information from literature has shown that an interaction between solid particles and gas bubbles explains the physical phenomena which take place in three-phase systems. For air/water systems it was found that solid particles smaller than 3-4 mm tend to increase the bubble size by promoting bubble coalescence. Particles greater than 3-4 mm result in bubble disintegration, and thus smaller bubbles.

The literature search has identified three major models describing the holdup of the phases in gas/liquid/solid systems. These were proposed by Ostergaard, Darton and Harrison, and Bhatia and Epstein. Because validation of these models requires information not currently available in the literature, no final model selection can be made at this time. It is the objective of the work to be conducted by Amoco to select a model as information is generated from the Amoco experimental program.

This program will be based on experimental techniques extensively reviewed in this report. Techniques using both external and internal measuring devices are discussed. The external techniques include gamma-ray scans, sonic methods, and radioactive tracers. Techniques internal to the reactor include light impedance and conductivity probes.

The literature search has also reviewed the effect of temperature, particle volume fraction, and particle size distribution on slurry viscosity.

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IAV/EMB/DFT/CCW/ml

NOMENCLATURE

		Typical Units
A	Cross-sectional area of column	cm^2
C_D	Drag coefficient for single particle or bubble	--
C_{DM}	Drag coefficient for multi-particle system	--
d	Particle diameter	cm
$\bar{d}$	Average particle diameter	cm
d_e	Equivalent spherical diameter of bubble	cm
d_p	Diameter of a circle if the same area as the projected particle when lying in its most stable position	cm
d_s	Diameter of a sphere with the same volume as the particle	cm
d_{sm}	Sauter-mean bubble diameter	cm
D	Bed or tube diameter	cm
D_c	Diameter of capillary	cm
f	Frequency of formation of bubble cluster	sec^{-1}
Fr	Froude number	--
g	Acceleration of gravity	cm/sec^2
G	Dimensionless group	--
H_{GL}	Three-phase bed height	cm
H_L	Liquid/solid bed height	cm
j_l	Liquid flux	$gm/cm^2\ sec$
j_l^*	Dimensionless liquid flux	--
$\bar{k}$	Average of wake volume to bubble volume ratio	--
K	Shape factor	--
K'	Effective hydrodynamic volume of particle	cm^3
l	Particle length	cm
M	Morton number	--
M'	Rheological parameter	$gm/cm\ sec^{n'-2}$

		Typical Units
n	Richardson-Zaki index or exponent in ideal bubbly flow regime models	--
n'	Rheological parameter	--
Q_g	Gas volumetric flow rate	cm^3/sec
r	Particle or bubble radius	cm
r^*	Dimensionless particle radius	--
r_e	Equivalent spherical bubble radius	cm
r_o	Orifice radius	cm
R	Radius of curvature	cm
Re	Particle Reynolds number	--
Re_b	Bubble Reynolds number	--
Re_f	Minimum fluidization particle Reynolds number	--
Re_m	Reynolds number for multi-particle system	--
Re_t	Particle Reynolds number based on U_t	--
U_b	Bubble rise velocity	cm/sec
U_g	Superficial gas velocity	cm/sec
U_l	Superficial liquid velocity	cm/sec
U_m	Mean velocity	cm/sec
U_r	Relative velocity between particles and liquid	cm/sec
U_s	Gas/liquid slip velocity	cm/sec
U_t	Terminal velocity of an isolated particle or bubble	cm/sec
U_{lo}	Superficial liquid velocity at incipient fluidization	cm/sec
U_{sl}	Velocity of gas slug	cm/sec
U_l'	Superficial liquid velocity in the particulate fluidized phase in a three-phase system	cm/sec
v_b	Bubble volume	cm^3

		Typical Units
v_{CD}	Gas drift flux	cm/sec
We	Weber number	--
X_k	Ratio of solids holdup in wake to solids holdup in particulate phase	--
Greek		
β	Number of small bubbles forming a cluster	--
ϵ	Bed voidage	--
ϵ_g	Volume fraction of gas	--
ϵ_1	Volume fraction of liquid	--
ϵ_s	Volume fraction of solids	--
ϵ_w	Volume fraction of wake phase	--
δ	Pore diameter of gas distributor	cm
ρ_g	Gas density	gm/cm^3
ρ_s	Density of particles	gm/cm^3
ρ_1	Density of liquid	gm/cm^3
ρ_b	Density of fluidized bed	gm/cm^3
τ_w	Wall shear stress	$dynes/cm^2$
μ_e	Effective viscosity	poise
μ_1	Liquid viscosity	poise
σ	Surface tension	dynes/cm
λ	Wavelength of disturbance	cm
ϕ	Solids volume fraction	--

TABLE I

CORRELATIONS FOR THE EXPANSION OF LIQUID FLUIDIZED BEDS

Author	Solids	Equation	Range of Applicability
Richardson and Zaki (6)	Spherical particles	$\epsilon_1^n = U_1/U_t$ where:	
		$n = 4.65 + 20\ d/D$	$Re_t < 0.2$
		$n = (4.4 + 18\ d/D)Re_t^{-0.03}$	$0.2 < Re_t < 1.0$
		$n = (4.4 + 18\ d/D)Re_t^{-0.01}$	$1 < Re_t < 200$
		$n = 4.4\ Re_t^{-0.1}$	$200 < Re_t < 500$
		$n = 2.4$	$Re_t > 500$
Richardson and Zaki (6)	Glass or steel cylinders and steel plates	$\epsilon_1^n = U_1/U_t$ $n = 2.7\ K^{0.16}$ where: $K = (\pi/6)d_s^3/d_p^3 = \left(\frac{\pi}{4}\right)^{5/2}\left(\frac{d}{l}\right)^{1/2}$ (for a cylinder)	$Re_t > 500$
Fouda and Capes (4)	Irregularly shaped particles	$(1 - K'\epsilon_s)^n = U_1/U_t$ where: n = same as in Richardson-Zaki correlation $K' = 1$ for spheres $K' = 1.17$ to 1.43 for equi-dimensional bud irregularly shaped particles	Same as in Richardson-Zaki correlation
Barnea and Mizrahi (1)	Spherical particles	$C_{DM} = \left(0.63 + \frac{4.8}{\sqrt{Re_m}}\right)$ where: $Re_m = Re\left(\frac{U_r/U_t}{\exp(5\epsilon_s/3(1-\epsilon_s))}\right)$ $C_{DM} = C_D\left(\frac{U_r}{U_t}\right)^2\left(\frac{1-\epsilon_s}{1+\epsilon_s^{1/3}}\right)$ $\frac{U_r}{U_t} = \frac{1}{1+\epsilon_s^{1/3}}$	$10^{-3} < Re_m < 3 \times 10^4$

(Table Continued)

TABLE I

CORRELATIONS FOR THE EXPANSION OF LIQUID FLUIDIZED BEDS

-2-

Author	Solids	Equation	Range of Applicability
Wallis (9)	Spherical particles	$j_1^* = 2/9\ r^{*2} \epsilon_1^{4.7}$	$Re_m < 1.5$
		$j_1^* = 0.307\ r^{*1.21} \epsilon_1^{3.47}$	$1.5 < Re_m < 100$
		$j_1^* = 0.693\ r^{*0.858} \epsilon_1^{2.92}$	$100 < Re_m < 1080$
		$j_1^* = 2.5\ r^{*1.2} \epsilon_1^{2.35}$	$1080 < Re_m$

where:

$$j_1^* = j_1\left(\frac{\rho_1}{\mu_1 g\ (\rho_s-\rho_1)}\right)^{1/3}$$

$$r^* = \left(\frac{\rho_1 g(\rho_s-\rho_1)}{\mu_1}\right)^2$$

IAV/ml
2/20/78

TABLE II

EXPERIMENTAL CONDITIONS FOR LIQUID/SOLID FLUIDIZATION OF CYLINDRICAL PARTICLES

Author	Solids	Particle Dimensions, In.	Liquid	Visco-sity (CP)	Bed Dia., In.
R.Wolk (HRI) (202)	Nalco-Mo Catalyst No. 471	Diameter: 0.025,0.050,0.063 Length: 1/8	Heptane	0.5	5
		Diameter: 0.025, Length 1/8	Heptane	0.5	1
		Diameter: " " "	Water	1.0	1
		Diameter: " " "	Isopropyl Alcohol	2.43	1
		Diameter: " " "	Transformer Oil	9.6	1
		Diameter: " " "	Linseed Oil	38.5	1
R. T. Struck, et al, OCR Report, 1968 (205,206)	UOP-S-6 Spherical Catalyst Beads	Diameter: 1/16	Diethylbenzene	0.87	3
Blum and Toman (66)	Harshaw Ni-0104-101	Diameter: 1/8; Length: 1/8	Light Mineral Oil	0.137 at 500°F	4
	CCI C150-1-02	Diameter: 3/16; Length: 3/32			
	CCI C150-1-02	Diameter: 3/16; Length: 3/16			

IAV/ml
2/20/78

TABLE III

TERMINAL VELOCITY OF ISOLATED BUBBLES IN LIQUIDS

Region	Terminal Velocity, U_t	Range of Applicability
1	$\frac{2r_e^2(\rho_1 - \rho_g)g}{9\mu_1}$	$Re_b < 2$ where Re_b bubble Reynolds number = $\frac{2\rho_1 U_t r_e}{\mu_1}$
2	$0.33g^{0.76}\left(\frac{\rho_1}{\mu_1}\right)^{0.52} r_e^{1.28}$	$2 < Re_b < 4.02M^{-0.214}$ where M Morton Number = $\frac{g\mu_1^4}{\rho_1\sigma^3}$
3	$1.35\left(\frac{\sigma}{\rho_1 r_e}\right)^{1/2}$	$4.02M^{-0.214} < Re_b < 3.10M^{-1/4}$ or $16.32M^{0.144} < G < 5.75$ where $G = \frac{g\ r_e^4 U_t^4 \rho_1^3}{\sigma^3}$
4	$1.18\left(\frac{g\ \sigma}{\rho_1}\right)^{0.25}$	$3.10\ G < Re_b$ $5.75 < G$

Source of Information: Peebles, F. N., and Garber, H. J., "Studies on the Motion of Gas Bubbles in Liquids," Chemical Engineering Progress, 49, 2 (1953).

IAV/ml
2/20/78

TABLE IV

RISE VELOCITY OF SINGLE BUBBLES IN FLUIDIZED BEDS: EXPERIMENTAL CONDITIONS

Investigator	Liquid	Solid (Dimension)	Bubble Equivalent Diameter	Column Size
Darton and Harrison (71)	Water	Sand (0.5 and 1 mm)	5-25 mm	22.9 cm dia.
Masimilla, et al. (85)	Water	Silica Sand (0.22 mm) Glass Beads (0.79,1.09 mm) Iron Sand (0.26 mm)	0.1-1.0 in.	3.4 x 2.4 in.
Verbitskii and Vakhrushev (108)	Water	Polystyrene (0.45 mm) Glass Particles (0.32 to 1.47 mm)	4.0-6.6 mm	5.75 cm 10.5 cm
Henriksen and Ostergaard (77)	Water Aqueous Glycerol Aqueous Glycerol and Methanol	Glass Beads (0.2,1,3 mm)		0.8 x 39.5 cm

DFT/ml
2/20/78

TABLE V

EXPERIMENTAL CONDITIONS FOR BUBBLE COALESCENCE

Investigator	Liquid	Gas	Solid	Solid Dimension (mm)	Bed Diameter (mm)	Character of Bed
Ostergaard (95)	Water	Air	Sand	0.64	250 x 250	Coalescing
Massimilla, et al. (85)	Water	Air	Sand	0.22,0.26	86 x 61	Coalescing
	Water	Air	Glass Beads	0.79,1.09	86 x 61	Coalescing
Viswanatan, et al. (109)	Water	Air	Quartz Particles	0.649,0.928	50.8	Coalescing
	Water	Air	Glass Beads	4.0	50.8	Non-Coalescing
Adlington and Thompson (64)	Water	-	Sand	3.0	76.0	Coalescing
	White Spirit	-	Alumina	0.3-3.0	76.0	Coalescing
Lee (82)	Water	Air	Glass Beads	6	-	Non-Coalescing

DFT/ml
2/20/78

TABLE VI

RISE VELOCITY OF BUBBLE SWARMS IN FLUIDIZED BEDS: EXPERIMENTAL CONDITIONS

Investigator	Gas	Liquid	Solid (Dimension)	Column Size
Rigby, et al. (100)	Air	Water	Glass (0.12,0.29,0.47 mm) Sand (0.775 mm)	10 cm Diameter
Kim, et al. (78)	Air	Water	Glass Beads (6 mm) Irregular Gravel (2.6 mm)	26 x 1 Inch
Kim, et al. (79)	Air	Various	Glass Beads (1,6 mm) Irregular Gravel (2.6 mm)	26 x 1 Inch

DFT/ml
2/20/78

TABLE VII

SUMMARY OF DATA FOR GAS/LIQUID/SOLID FLUIDIZATION

Investigators	System	Particle Size	Experimental Unit	Parameters Studied	Quantities Measured
1) Razumov, Manshilin, Nemets (98)	Air/Water/Sand Air/Water/Slag Beads	0.493 to 1.27 mm	300 mm Diameter Column	U_g, U_l	ϵ_s
2) Michelsen, Ostergaard (86)	Air/Water/Glass Beads	1,3,6 mm	6" Diameter Column	U_g, U_l, Particle Size	ϵ_s, ϵ_l
3) Dakshinamurty, Subramanyam, Rao (68,69)	Air/Water/Various Spherical Particles Air/Kerosene/Various Spherical Particles	1.06 to 6.8 mm	56 mm Diameter Column	Particle Size and Density σ, U_g, U_l	ϵ_s
4) Viswanathan, Kakai, Murti (109)	Air/Water/Quartz Particles Air/Water/Glass Beads	0.928,0.649 mm 4 mm	50.8 mm Diameter Column	U_g, U_l, Particle Size	ϵ_l, ϵ_g
5) Kim, Baker, Bergougnou (78)	Air/Water/Glass Beads Air/Water/Irregular Gravel	6 mm 2.6 mm	26 x 1" Rectangular Channel	U_g, U_l	ϵ_l, ϵ_g, Bubble Size and Velocity
6) Kim, Baker, Bergougnou (80)	Air-Water/Acetone-Glass Beads Air-Water/Acetone-Irregular Gravel Air-Sugar/Water-Glass Beads Air-Carboxymethyl Cellulose/Water-Glass Beads Air-Sugar/Water-Irregular Gravel Air-Carboxymethyl Cellulose/Water-Irregular Gravel	1,6 mm 2.6 mm 1,6 mm	26 x 1" Rectangular Channel	μ_l, σ, U_l, U_g	ϵ_g, ϵ_l
7) Blum and Toman (66)	Nitrogen/Light Mineral Oil	See Table II	4" Diameter Column	U_l, U_g, μ_l	ϵ_s
8) Nemets, Razumov, and Manshilin (87)	Air/Water/Sand Air/Heptane/Sand Air-Water/Glycerol-Sand	0.820 mm	90 mm Diameter Column	U_l, U_g, μ_l	ϵ_l, ϵ_g
9) Bruce, Revel-Chion (67)	Air/Water/Glass Spheres	2,4,6,8 mm	46.3 mm Diameter Column	U_l, U_g	ϵ_s, Bubble Size
10) Ostergaard, Theisen (90)	Air/Water/Glass Ballotini	0.28 to 2.2 mm	2 and 4" Diameter Column	U_l, U_g	ϵ_s

DFT/ml
2/20/78

TABLE VIII

EMPIRICAL CORRELATIONS FOR THREE-PHASE BEDS

Author	Correlation	Gas/Liquid	Solids (Dimension)	Column Diameter or Dimensions	Comments
Kim, Baker, Bergougnou (78)	$(\epsilon_1)_{U_g=0} - \epsilon_1 = 0.0025 \left(Fr_1 \frac{\rho_s}{\rho_1}\right)^{0.148} \left(Fr_g \frac{\rho_s}{\rho_s}\right)^{0.161} \left(\frac{Re_1}{Re_g}\right)^{0.259}$	Air/Water	Glass Beads (6 mm) Irregular Gravel (2.6 mm)	26" x 1"	Empirical, no consideration for bed contraction
	$(\epsilon_1)_{U_{g=0}} = 0.409(Fr_1\rho_s/\rho_1)^{0.193}(Re_1)^{0.074}$				
Kim, Baker, Bergougnou (80)	$(\epsilon_1+\epsilon_g) = 1.40(Fr_1)^{0.17}(We)^{0.078}$ (Expanding Beds)				Empirical for expanding and contracting beds
	$(\epsilon_1+\epsilon_g)_{U_{g=0}} = 1.3(Fr_1)^{0.128}(We)^{0.073}\exp[0.31\, U_1/U_g(\epsilon_1)_{U_g=0}]$ (contracting beds)	Air/Sugar Solutions Air/Carboxymethyl Cellulose Solution Air/Water Acetone	Glass Beads (6,1 mm) Irregular Gravel (2.6 mm)	26" x 1"	
	$(\epsilon_1)_{U_g=0} = 1.353(Fr_1)^{0.208}(Re_1)^{-0.1}$				
	$\epsilon_1 = 1.54(Fr_1)^{0.234}(Fr_g)^{-0.088}(Re_1)^{-0.082}(We)^{0.092}$				
Dakshinamurty, Subrahmanyam, Rao (68,69)	$(\epsilon_g + \epsilon_1) = \left(K \frac{U_1}{U_t}\right)^m \left(\frac{\mu_1 U_g}{\sigma}\right)^n$ $n = 0.08$ $K = 2.12,\ m = 0.41,\ Re_t < 500$ $K = 2.65,\ m = 0.6,\ Re_t > 500$	Air/Water Air/Kerosine	Numerous Diameters 1.06 to 6.8 mm	56 mm Diameter	Empirical, no consideration for bed contraction
Blum, Toman (66)	$\frac{(\epsilon_g + \epsilon_1) - (\epsilon_1)_{U_g=0}}{1 - (\epsilon_1)_{U_g=0}} = f(U_g)$	Nitrogen/Light Mineral Oil	Cylinders Dia. Length 1/8" 1/8" 3/16" 3/32" 3/16" 3/16"	4" Diameter	Empirical, no consideration for bed contractions
Razumov, Manshilin, Nemets (98)	$\epsilon_s = 0.578 - 3.198\, U_1 - 0.538\, U_g$ $\epsilon_1 = 0.422 + 0.135\, U_1/\bar{d}^{\,0.582} - 1.82\, U_g$ $\epsilon_g = K(1 - \epsilon_s)^{2.09}(U_g/U_1)^{0.78}$	Air/Water	Sand, Slag Beads 0.49 to 1.27 mm	300 mm	Empirical, no consideration for bed contractions

DFT/ml
2/20/78

TABLE IX

HRI THREE-PHASE DATA

	Title	Gas/Liquid	Particle Size		Bed Diameter Inches
			Diameter Inches	Length Inches	
1)	R. Wolk, "Variables Affecting the Performance of an Ebullated Bed," May 4, 1961 (202)	Nitrogen-Heptane	1/32	1/8	5/8,1,1.5,2,5,6
			1/16	1/8	
			5/64	1/8	
2)	R. Wolk, "Gas/Liquid/Solid Fluidization," June 18, 1962 (203)	Nitrogen-Heptane	0.025	3/16	0.625,1.0,1.5,2,5,6
			0.050	3/16	
			0.063	3/16	
		Nitrogen-Isopropyl Alcohol	0.025	3/16	1.0
3)	W. Volk, C. Weber, "Catalyst Concentration Measurements in Heptane-N_2 Ebullated Bed Studies" (201)	Nitrogen-Heptane	Mesh Size Range 74 to 220		3,6

DFT/ml
2/20/78

TABLE X

SYNOPSIS OF HRI REPORTS

Title	Objective
1) R. Wolk, "Variables Affecting the Performance of an Ebullated Bed," May 4, 1961 (202)	The effects of liquid flow rate, gas flow rate, tube diameter, particle diameter, and liquid density and viscosity on the expansion of a catalyst bed were investigated. It was found that: 1) Decreasing the diameter of a particular type of particle increased the bed expansion. 2) Increasing the length of a particle decreased the bed expansion. 3) At a fixed tube diameter the expansion increased with gas rate. 4) Expansion declines at a given liquid and gas rate as the tube diameter increases. 5) Expansion increased with increasing liquid viscosity. 6) Expansion increased with decreasing particle density.
2) R. Wolk, "Gas/Liquid/ Solid Fluidization," June 18, 1962 (203)	Effect of gas flow rate on the expansion of a liquid fluidized bed was studied. It was claimed that introduction of gas at a constant liquid rate increased the bed expansion. A comparison with liquid/solid expansion data indicated that the increased expansion is due to the volume occupied by the gas. Effects of solid particle size, tube diameter, liquid rate, and gas rate on bed expansion were studied. Gas/liquid systems were also studied.
3) W. Volk, C. Weber, "Catalyst Concentration Measurement in Heptane-N_2 Ebullated Bed Studies" (201)	Catalyst concentrations were determined as a function of vertical distance in 3" and 6" plastic tubes and in the H-Oil pilot plant. Concentrations were determined in the plastic tubes by withdrawing samples (liquid/solid) and determining the catalyst concentration. Gamma-ray absorption was used to measure the concentrations in the H-Oil pilot plant. A sharp decline in catalyst concentration indicates a clean transition between a dense bed and a dilute bed and indicates "good" ebullation. In the plastic units it was found that increasing liquid and gas rates, increasing tube diameter, and lower catalyst bulk density leads to a poorer transition.

(Table Continued)

TABLE X

SYNOPSIS OF HRI REPORTS

-2-

Title	Objective
4) Zenz' Report, June 3, 1976 (204)	PDU bed expansion data are analyzed to determine if they can be correlated in terms of a drag coefficient vs. Reynolds number relationship for single particles, as proposed by Barnea and Mizrahi (1). The drag coefficients and Reynolds numbers are modified to take into account catalyst concentration. Zenz contends that the data do fit this kind of model.

DFT/ml
2/20/78

TABLE XI

GENERALIZED WAKE MODEL OF BHATIA AND EPSTEIN (65)

1) Liquid mass balance:

$$\epsilon_l = \epsilon_w(1-X_k) + \epsilon_l'(1 - \epsilon_g - \epsilon_w + X_k\epsilon_w) \qquad (1)$$

2) $\epsilon_l + \epsilon_g + \epsilon_s = 1$ (2)

3) Richardson and Zaki relation:

$$\epsilon_l' = \left[\frac{U_l - \frac{U_g}{\epsilon_g}\epsilon_w(1 - X_k)}{U_t(1 - \epsilon_g - \epsilon_w)}\right]^{1/n} \qquad (3)$$

4) $$\frac{U_g}{\epsilon_g} = \frac{U_l + U_g + \epsilon_l'(1 - \epsilon_g - \epsilon_w)U_s}{1 - \epsilon_s} \qquad (4)$$

5) Empirical relation for ϵ_w:

$$\frac{\epsilon_w}{\epsilon_l} = \frac{\epsilon'_w}{\epsilon'_l}(1 - \epsilon_s)^3 \qquad (5)$$

6) Empirical relations for U_s (slip velocity):

a) Bubble flow regime:

$$U_s = \frac{U_t \ \mathrm{Tanh}(0.25\epsilon_g - 1/3)}{\epsilon_l} \qquad (6)$$

b) Slug flow regime:

$$U_s = \frac{0.2(U_l + U_g + 0.35\sqrt{gD})}{\epsilon_l}$$

X_k = Ratio of solids holdup in wake to solids holdup in particulate phase.
ϵ_k = Wake volume fraction
ϵ_l' = Liquid holdup in two-phase liquid/solid system
ϵ_w' = Wake holdup in two-phase gas/liquid flow

Unknowns: ϵ_l, ϵ_g, ϵ_s, ϵ_w, ϵ_l', U_s

DFT/ml
2/20/78

TABLE XII

GAMMA-RAY SOURCES

Isotope	Half-Life	Principal Gamma Rays
Na-24	15 h	1.4, 2.8 Mev
La-140	40 h	2.5, 1.6 Mev
Radium	1590 y	Avg 0.8 Mev
Co-60	5.22 y	1.2, 1.3 Mev
Ta-182	111 d	1.2 MeV
Ir-192	74 d	Avg 0.4 Mev
Cs-137	33 y	0.66 Mev
Cs-134	2.3 y	Up to 0.7 MeV
Tm-170	129 d	84 kev (X-rays)
Am-241	470 y	60 kev (X-rays)
Eu-155	1.7 y	87 kev (X-rays)
Sm-153	2 d	75 kev (X-rays)

Source: Eastwood, W. S., "The Development of Gamma Radiography," Proceedings of the International Conference on Peaceful Uses of Atomic Energy, 15, 177 (1955)

2/20/78

TABLE XIII

ADVANTAGES AND LIMITATIONS OF COMMONLY USED DETECTORS

	Detector	*Temp. Range*	*Useful Life*	*Dead Time*	*Efficiency**	*Comments*
1.	Pulse Ion Chamber	Very Wide	Infinite	$< 1\ \mu s$ for fast chamber	$\sim$100% for α's and fission prod. Low for γ's or β's.	Used for α spectrometry and as sensitive neutron detector
2.	Avg. Ion. Chamber	Very Wide	Infinite	Time constant depends on size, load resistor & circuitry	Depends on constr. mtl, fill pressure	Air equiv. used for pocket dosemeter; rad. survey; with electrometer & fill chamber use for C^{14} & H^3
3.	Proportional Counter	Normal 200°F Special to 1000°F	10^{10} counts for sealed tube. Infinite for flow counter.	1 – 2 μs	End window type 100% for β's 1% for γ's 100% for α's. BF_3 filled 20–50% for thermal neutrons, low for gammas.	Flow, windowed type for precision, reproducible beta counting. For α/β discrimination. Requires stable HVPS & linear amp.
4.	Organic Quench G-M Counter	−20°F to 250°F	10^9 counts	100–300 μs (depends on size)	$>99\%$ for β or α 1–2% for γ's	Inexpensive, easy to use (provides $\frac{1}{4}$ volt pulses) Commonly used for portable survey meters, lab counting.
5.	Halogen Quench G-M Counter	−70°F to 170°F	Infinite	100–300 μs (longer than same size organic quench G-M)	80–90% for β 1–2% for γ's.	Widely used for survey instr., some use as lab counter; useful for go-no-go Indus. Applic. such as level gages.
6.	Scin. Counter with NaI(Tl)	170°F set by evap. of photocathode	Infinite	2.5×10^{-7} sec.	High for γ's (or β) e.g. 40% for 1 mev γ in 1" × 1"	Excellent γ detector can be used with spectrometer for energy determination.
7.	Scin. Counter with ZnS (Ag)	170°F set by evap. of photocathode	Infinite	10^{-6} sec.	$\sim$100% for α. Very low for β or γ.	Excellent α detector. $\frac{1}{4}$ volt pulses can directly drive scaler.
8.	Scin. Counter with stilbene (or anthracene)	170°F set by evap. of photocathode	Infinite	3×10^{-8} sec.	$\sim$100% for β use $\frac{1}{16}$" thick to minimize γ sens.	Excellent β detector similar to NaI in need for preamp. ahead of $\frac{1}{4}$ volt input scaler.
9.	Liquid Scin. Counter	Room temp for C^{14} — 10 to −20°F for H^3	Infinite	3×10^{-8} sec.	75% for C^{14}. 5–20% for H^3 (depends on type and size of sample).	Widely used for H^3 and C^{14} can be used as 4-pi alpha counter and with flowing sample.
10.	Photographic Film	Room Temp. and below	—	—	As dosimeter can detect 30–50 mr to 100 r.	Use for autoradiography and personnel monitoring.
11.	Chemical Dosimeters	Depends on type of dosimetry system	—	—	High for β and γ. Can load with B^{10} or Li^6 for neutrons.	Used primarily for high-level dosimetry.

*For Radiation entering the detector.