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**Development of A Natural Gas Systems
Analysis Model (GSAM)**

Annual Report

February 1994

Work Performed Under Contract No.: DE-AC21-92MC28138

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
ICF Resources, Incorporated
Fairfax, Virginia

MASTER

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Abstract

Lacking a detailed characterization of the resource base and a comprehensive borehole-to-burnertip evaluation model of the North American natural gas system, past R&D, tax and regulatory policies have been formulated without a full understanding of their likely direct and indirect impacts on future gas supply and demand. The recent disappearance of the deliverability surplus, pipeline deregulation, and current policy debates about regulatory initiatives in taxation, environmental compliance and leasing make the need for a comprehensive gas evaluation system critical. Traditional econometric or highly aggregated energy models are increasingly regarded as unable to incorporate available geologic detail and explicit technology performance and costing algorithms necessary to evaluate resource-technology-economic interactions in a market context.

The objective of this research is to create a comprehensive, non-proprietary, microcomputer model of the North American natural gas system. GSAM explicitly evaluates the key components of the natural gas system, including resource base, exploration and development, extraction technology performance and costs, transportation and storage and end use. The primary focus is the detailed characterization of the resource base at the reservoir and sub-reservoir level and the impact of alternative extraction technologies on well productivity and economics. GSAM evaluates the complex interactions of current and alternative future technology and policy initiatives in the context of the evolving gas markets. Scheduled for completion in 1995, a prototype is planned for early 1994.

ICF Resources reviewed relevant natural gas upstream, downstream and market models to identify appropriate analytic capabilities to incorporate into GSAM. We have reviewed extraction technologies to better characterize performance and costs in terms of GSAM parameters.

We have developed databases for the gas resource base, costs, exploration, pipeline capacity and volumes, alternative sources and end-use. Although an accurate reservoir-level resource database is not yet available, we have generated a synthetic reservoir-level database that broadly reflects the geological characteristics and volumes by region, depth and resource type. This database is being used to assist in model testing and validation.

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I. Introduction

A. Research Objective

The objective of this research is to create a comprehensive, non-proprietary, microcomputer model of the North American natural gas system. The model is to explicitly evaluate key components of the natural gas system, including resource base, exploration and development, extraction technology performance and costs, transportation and storage and end use. It will be used to evaluate alternative METC R&D strategies and to estimate the impact of federal energy and environmental policy initiatives on domestic natural gas potential. (The three-year project has been accelerated to provide a working prototype model by early 1994.)

B. Background

Recent dramatic changes in natural gas markets have significant implications for the scope and direction of DOE's upstream as well as downstream natural gas R&D. Open access transportation changes the way gas is bought and sold. The end of the gas deliverability surplus requires increased reserve development above recent levels. Increased gas demand for power generation and other new uses changes the overall demand picture in terms of volumes, locations and seasonality.

DOE's Natural Gas Strategic Plan requires that its R&D activities be evaluated for their ability to provide adequate supplies of reasonably priced gas. Potential R&D projects are to be evaluated using a full fuel cycle, benefit-cost approach to estimate likely commercial, as well as technical, success. To assure R&D projects are evaluated on a comparable basis, METC has undertaken the development of a comprehensive natural gas technology evaluation framework. Existing energy systems models lack the level of detail required to estimate the impact of specific technologies across a range of geological and market settings.

Gas Systems Analysis Model (GSAM) research during the reporting period developed and implemented this comprehensive, consistent natural gas evaluation framework. Rather than a distinct research activity, however, it represents the integration of many prior and ongoing natural gas research

efforts. When complete, GSAM will incorporate the most current resource base description, reservoir modeling, technology characterization and other geologic and engineering aspects developed through recent METC and industry gas R&D programs.

This annual report summarizes the purpose, activities and results of these three research activities during the period of performance, June 22, 1992 to June 21, 1993.

II. Research Methodology

A. Overview

GSAM is being developed in two phases. Phase I includes the review of existing natural gas extraction technologies, a review of current upstream natural gas computer models and the development of a comprehensive natural gas systems evaluation framework. Phase I concludes with the development, testing and peer review of a working prototype GSAM model and reservoir database, scheduled for completion in early 1994. Phase I model development and partial validation of some system components will be completed on schedule. Full system validation, however, cannot be completed until a reservoir database becomes available (expected by early Spring 1994).

Phase II encompasses preliminary use of GSAM to support METC R&D strategy development and estimate impacts of federal policy initiatives on the domestic gas industry. METC will set priorities and direct selected GSAM modeling enhancements, to be concluded in June 1995. At that time ICF Resources will install GSAM at METC and train METC staff.

B. Design Philosophy

GSAM models the upstream natural gas system at the level at which operators make investment and technology selection decisions: the individual reservoir. Each component of the upstream evaluation methodology accommodates this level of detail:

- The *resource base* is characterized as individual reservoirs with average effective reservoir properties and, for known reservoirs, complete drilling and production histories.
- *Technology* is characterized in terms of the explicit physical and cost parameters that affect gas contact, flow rates and ultimate recovery, and the costs associated with applying a group of technologies in the specified reservoir setting.
- *Production modeling* accounts for unique interactions of geology, technology and operating practices that influence gas recovery rate and ultimate volume for individual wells and reservoirs.

- *Project economics* are evaluated on an industry-standard after-tax pro-forma basis for both full and incremental project bases. Projects are costed at the level of the commonly used authorization for expenditure (AFE) and evaluated under explicit timing and amounts of capital, operating and tax costs and revenue streams.
- *Decision-making* incorporates the inherent uncertainties and inefficiencies in technology performance and gas markets.

Analysis of downstream issues such as gas demand, transmission, storage, imports, additional gas sources, pipeline capacity additions and interfuel competition are aggregated to the regional level.

C. Research Plan

Design and development of a model of this complexity required a detailed research plan and corresponding management controls. For this project, we developed a research Work Breakdown Structure and integrated this into a critical path method (CPM) management plan. Appendix A contains the summary Work Breakdown Structure developed for Phase I of this research.

This research was completed in three distinct activities (1) Review Technologies, (2) Review Models, and (3) Develop GSAM Methodology. Complete details on each of these activities is reported in the next three sections. Greater detail will be provided in separate topical reports on each activity.

Each of these components will incorporate the capability to evaluate the inherent uncertainties in resource characterization, technology application, reservoir performance, market economics and operator decision-making. Two important benefits of including explicit risk analysis in GSAM are to provide insights into the value of better information and to estimate the range of possible outcomes of current or proposed policies under alternative resource, technology or market scenarios.

III. Review Technologies

A. Purpose and Scope

The purpose of this task was to review exploration, development and production technologies in the context of the natural gas resources against which they will be applied. Our strategy was to select and analyze priority upstream natural gas technologies, then collect and evaluate data on performance, cost and current applications. The work was conducted in four subtasks:

1. Establish Technology Selection Criteria

We first compiled a list of key natural gas technologies. This required a review of in-house technology assessments and reviews of recent technology advances in the published literature. We also acquired from METC a list of current technologies targeted by federal R&D as well as the most recent Natural Gas Strategic Plan and Multi-Year Program Crosscut Plan. Additional materials on critical gas technologies were compiled and evaluated from GRI and from the National Petroleum Council Gas Study technology working group, to which ICF Resources was an advisor.

We then grouped technologies into preliminary categories of similar characteristics, both in terms of impact on gas discovery and production as well as research focus:

- Exploration (e.g., seismic)
- Formation evaluation (e.g., MWD, logging)
- Drilling (e.g., horizontal, underreaming)
- Completion (e.g., perforations, subsea, cavity)
- Stimulation (e.g., hydraulic, tailored pulse loading)
- Gas processing (e.g., dehydration, sweetening)
- Storage (e.g., hysteresis, cushion gas)
- Transmission (e.g., metering, compression)

Each technology was then characterized by applicability to GSAM and to industry for the following criteria:

- Soundness of theoretical basis on which to model
- Availability of cost and performance data
- Extent of commercial potential
- Appropriateness for DOE role (vs. industry) in R&D
- Technical efficiency improvement (e.g., relative to traditional methods)
- Cost reduction potential

A technology ranking protocol was established to set priorities for evaluation of selected technologies. A sample list of technologies was developed and submitted to METC for review.

2. Rank Technologies For Evaluation

We incorporated METC comments into a revised ranking protocol and prepared final guidelines for characterization of each technology. We ranked technologies in each category (e.g., exploration, drilling, completion) and collected summary/aggregated data for preliminary evaluation. Technologies were also ranked by GSAM Phase (e.g., I or II, the latter to require deferral of detailed evaluation until it was assured that these technologies had a significant impact on gas supply and demand relative to other technologies modeled). The final list of technologies were submitted to METC for review.

3. Collect Data on Current Technology Applications and R&D in Progress

The next step was to conduct a detailed literature search to collect the following data:

- Technology descriptions
- Applications data (e.g., where now used, criteria for use, limitations)
- Performance data (e.g., especially compared to traditional methods)
- Cost data (e.g., research vs. commercial costs)
- Vendor data (e.g., industry leaders vs. licensees)

- Estimates of commercial potential (e.g., expected use by 2000)
- Accepted methods of modeling/analysis (e.g., simulator results)
- Competing technologies/practices (e.g., cheap infill wells vs. longer fractures)

4. Tabulate Technology Performance Data

We then contacted operators and vendors for additional data and prepared tables of technology characterization:

- Technical performance (e.g., absolute or compared to traditional)
- Cost (e.g., low or high capital/operating relative to traditional)
- Applications (e.g., none, limited, moderate, extensive)
- Commercial potential (e.g., extensive or limited)
- R&D status (e.g., active vs dormant, who does R&D)

B. Results and Discussion

The generic technology categories selected for GSAM modeling are shown in Table 1. These categories will be used to evaluate alternative levels of performance and cost for a suite of technologies and processes in each category, rather than the performance of individual tools and processes specific to individual settings. This provides an appropriate level of detail for this stage of model development but retains a level of aggregation that allows the user to intuitively evaluate the plausibility of the model results. This list will evolve as model development proceeds.

Table 1
Preliminary GSAM Technology Evaluation Categories

<u>GSAM Technology Category</u>	<u>Example Technology Subcategories</u>
Exploration	Surveys Seismic Subsurface Analysis
Drilling	Rigs Drillstring Fluids Processes
Reservoir Characterization	Open Hole Logging Cased Hole Logging Coring Well Testing Mechanical Properties Testing Geochemical Analysis
Completion	Casing Cementing Perforation Configuration
Stimulation	Acidizing Hydraulic Fracturing - Proppants Hydraulic Fracturing - Fluids Hydraulic Fracturing - Additives Explosive Combustion
Production	Produced Water Treatment and Disposal Compression Facilities Operation and Maintenance
Processing	Field Dehydration Field Sweetening Plant Fractionation
Reservoir Management	Deepening Workover Abandonment
Transmission	Storage Site Access Performance Requirements Operation and Maintenance Data Collection and Reporting

IV. Review Models

A. Purpose and Scope

This task incorporated past government research and model development efforts into GSAM to assure that GSAM has capabilities at least as sophisticated as other publicly available models (within the design objectives and constraints of GSAM). The strategy was to review publicly available, microcomputer-based, non-proprietary models of natural gas resources and technologies for adaptation into GSAM. Evaluate models at various levels of detail, including (1) true systems models, (2) limited scope systems models (e.g., TORIS, TGAS), and (3) non-proprietary reduced form technology and reservoir models.

Due to the large number of models available and the range of specialized applications for which they were designed, we limited our review of models to those that were most applicable to integrating into GSAM. Selection criteria for reviewing models were established:

- Accessibility (e.g., only model available or adapted from current versions)
- Ease of use (e.g., must be commercial and not require a lot of additional research)
- Scale (e.g., appropriate for reduced form model and data availability)
- Data requirements (e.g., data resolution, quality and volume required)
- Scope (e.g., breadth of applicability to a variety of settings)
- Adaptability (e.g., general enough to assess a category of technologies)
- Documentation (e.g., does it exist, is it useful?)
- Model validity (e.g., has model been adequately validated?)
- Credibility (e.g., if known, how is the model generally viewed by industry?)
- Treatment of uncertainty (e.g., whether and how parameter uncertainty is addressed)

We then gathered model documentation and any published appraisals of these models. We evaluated reservoir models in terms of their consistency of implementation with currently accepted theory, accuracy of reduced form model against simulator (where appropriate), the validity of the model against field results (e.g., history match reservoir model) and an evaluation against full range of input parameters (e.g., boundary limits).

B. Results and Discussion

1. Natural Gas Market Models

For market models, we evaluated their strengths and weaknesses against the requirements of GSAM and prepared a summary description of each model. The market models reviewed (and their developers) were:

- GAMS and PROLOG Models (DOE/EIA), as part of NEMS
- Fossil2 (DOE/AES Corp./EEA Inc.)
- Hydrocarbon Supply Model (EEA/GRI)
- GRI North American Regional Gas Supply-Demand Model (DFI)
- North American Gas Market Model (ICF Resources)
- MARKAL Market Allocation Model (DOE Brookhaven National Laboratory)
- AGA-TERA Model (American Gas Association)
- AGAS Model (Alberta Research Council)
- MIT/North American Gas Trade Model (MIT)
- North American Gas Trade Model (Stanford)
- DRI Natural Gas Forecasting System
- WEFA Natural Gas Modeling System
- Rowse/University of Calgary Model

2. Natural Gas Reservoir Models

For reservoir models, we evaluated the theoretical rigor, validity and applicability for GSAM (either through development of comparable capabilities or adaptation into GSAM itself). We concentrated on models for unconventional gas resources, principally because reduced form modeling of gas desorption, diffusion and two-phase flow is more complex. We reviewed the literature and prepared a topical report on available reduced form reservoir models.

Models reviewed can be characterized as empirical, equilibrium (pressure dependent), or non equilibrium (pressure and time dependent) models. Because the focus of GSAM is to evaluate the influence of technology in terms of timing as well as effect on production rate or ultimate recovery, GSAM will primarily use non-equilibrium models.

To maximize consistency in evaluating technology and gas potential, reservoir modeling in GSAM will be consolidated into a single model structure. Although reservoir flow regions and technology characterization will vary by resource type, this design strategy will enhance model visibility and validation. For this reason, we have focused our review of reservoir models on the most complex reservoirs: coal, shale and geopressured brines.

Principal families of unconventional models reviewed include:

- GRUSSP
- COMETPC, COMET PC-3-D
- SUGAR, SUGAR MD (2-D)

V. Develop Methodology

A. Purpose and Scope

GSAM is segmented into separate Upstream and Downstream Modules linked by an Integrating Module (Figure 1). Modules may be run independently or as an integrated system. This structure provides the ability to examine extraction technology performance or economics of a reservoir, region, resource type or for the entire North American gas market.

B. Upstream Module

The Upstream Module estimates gas recovery and costs at the level of individual reservoirs. This section briefly describes the key aspects of resource base characterization, reservoir modeling, technology characterization and modeling, reservoir development, exploration, decisionmaking, treatment of uncertainty and risk, estimation of other gas supplies and the role of technology transfer. Table 2 shows

Figure 1
GSAM Structure

Table 2
Limitations of Traditional Natural Gas Modeling Analytical Approaches

Model Component	Traditional Systems Model Implementation	Applicability for METC
Resource Base Characterization	Typical reservoirs by region, resource category or depth	Fails to geologically describe range of reservoir settings influenced by technology
Reservoir Performance	Decline curve or R/P ratio tied to resource type	Cannot predict interaction of technology, geology and operating practices
Technology Performance	Performance improvement input as change in recovery or cost	Cannot evaluate impact of specific R&D initiatives on costs or recovery
Reservoir Development	Fixed pace and profile tied to field size	Ignores gas markets and technology options/constraints of operator
Exploration	Discovery process model applied to regionally aggregate field size distribution	Fails to accommodate specific technology changes in the context of changing undiscovered resource base characteristics
Decision-Making	Maximize producer profit	Appropriate, but assumes more efficient markets and information than are available
Uncertainty/Risk	Implicit or not addressed	Theory well developed but little systems model application in literature
Other Gas Supplies	Exogenous, often tied to input oil prices	Appropriate, but often inconsistent with oil and other gas markets and technology advances

the limitation of traditional approaches to upstream natural gas modeling that we addressed during GSAM design. Table 3 summarizes the approach taken in addressing each of these limitations.

The general analysis flow of the upstream portion of GSAM is shown in Figure 2. Raw resource data are transformed into a reservoir database, which will be used to evaluate, at the reservoir level, the impact of alternative technologies and policies on recovery potential.

Table 3
Upstream Modeling Features Incorporated Into GSAM

Components	Implementation in GSAM
Resource Base	Geologically characterized reservoirs (also at subreservoir detail)
Reservoir Performance	Suite of resource-specific, multiwell type curves
Technology Performance	Detail methodology to estimate parameter values for uses in reservoir models
Reservoir Development	Comprehensive evaluation and optimization of development options in context of geology, technology, costs and markets
Exploration	Traditional discovery process model based on explicit resource characterization with future ability to evaluate specific exploration technologies
Decision-Making	Projects initiated to maximize profit, accounting for explicit logistical constraints and market inefficiencies
Uncertainty/Risk	Can potentially be evaluated by a variety of mechanisms to examine impacts of uncertainty on decision making
Other Gas Supplies	Canadian supplies modeled like U.S., other exogenous estimates based on technology/economic assumptions corresponding to those used in GSAM

Figure 2
GSAM Upstream Analysis Flow

1. Resource Base Characterization

GSAM will incorporate a reservoir database of about 5,000 fully characterized producing reservoirs. Reservoir data will be derived from the Gas Information System (GASIS), currently under development by METC, or other sources. Although the validity and internal consistency of data for each reservoir will have been completed in the GASIS development process, GSAM will contain a complete set of default algorithms to assign values for missing or inconsistent reservoir properties.

Because GSAM evaluates individual reservoirs, the GSAM resource database will be developed from geological and engineering descriptions of known reservoirs. The core resource data to be used to develop the GSAM reservoir database are shown in Table 4. Each reservoir will be described in three general ways: (1) identification and location, (2) reservoir properties and, (3) development history. These data will be translated into a comprehensive and internally consistent reservoir database for use directly by GSAM.

GSAM evaluates three types of reservoirs: producing, discovered nonproducing and undiscovered. All reservoirs will be described in a common database format, although the characterization of each will depend on available data. In many cases reservoir level defaults data will be generated by transforming data from higher or lower levels of aggregation, all of which will be documented (Figure 2).

Producing reservoirs' ultimate recovery or flow rate may be increased by application of improved technology. Accurate characterization of reservoir properties and current depletion status are necessary to accurately estimate this potential using GSAM's reservoir models. GSAM and GASIS developers will work together to history match selected producing reservoirs to verify internal consistency between reservoir properties and production history.

Discovered, nonproducing reservoirs primarily represent reservoirs recently discovered but uneconomic to develop on a sunk cost basis. Because they are a potentially large source of low-cost reserve additions, accurate estimates of their number, size and characteristics are critical.

Undiscovered resources are defined in GSAM as typical reservoirs by field size within geological plays. Since known reservoirs to be described in GASIS are likely to adequately represent the range of geological settings that constitute reservoirs yet to be found, they provide acceptable analogs to characterize undiscovered resources. GSAM research in Phase II will develop a method to characterize these typical play and size-class specific reservoirs.

Table 4 - GSAM Resource Data Format

Variable ID	Variable Name	Symbol	Units	Description	Format	Notes
RD1000	GSAMID	none	none	unique GSAM ID reservoir code	8 I	include compressed ID codes
RD1010	SOURCE	none	none	source reservoir code	8 I	validation/update reference
RD1020	FLDNAM	none	none	field name	30 A	EIA Master List
RD1030	EIACOD	none	none	EIA field code	10 I	EIA Master List
RD1040	RSVNAM	none	none	reservoir name	30 A	EIA or state
RD1050	STATE	none	none	state	2 A	2 digit API code
RD1060	COUNTY	none	none	county name	3 A	3 digit API code
RD1070	PLYCOD	none	none	play code	4 I	NRG or GASIS play codes
RD1090	BSNCOD	none	none	basin code	3 I	PGC, USGS code
RD1130	GSAMSR	none	none	GSAM supply region	4 I	26 supply regions
RD1140	STATIN	none	code	initial development status	1 I	0 = undiscovered; 1 = disc/undevt; 2 = producing/partially developed; 3 = init devt complete; 4 = fully devt; 9 = abandoned
RD1150	LATLON	none	degr, min, sec	lat/long of reservoir centroid	15 I	DDDMSS-DDDMSS
RD1160	DEPCLS	none	none	depositional class	3 I	adapted from DOE oil classes
RD2000	RESCOD	none	code	resource type	2 I	1 = unconsolidated SS; 2 = consolidated SS; 3 = carbonate; 4 = coal; 5 = shale; 6 = hydrate
RD2010	TRAPTY	none	dimensionless	trap type	1 I	dominant trapping mechanism
RD2020	DRIVE	none	code	dominant drive type	1 I	1 = pressure depletion; 2 = water drive; 3 = desorption/depletion
RD2030	DEPTH	D	feet	depth	6.0 F	depth to top of formation
RD2040	GRSPAY	H	feet	gross pay thickness	4 I	gross formation interval
RD2050	NETPAY	h	feet	total net pay in designated formation	6.1 F	total net pay in designated formation

Table 4 - GSAM Resource Data Format (Continued)

Variable ID	Variable Name	Symbol	Units	Description	Format	Notes
RD2060	PAYDSP	none	dimensionless	pay dispersion	3.1 F	concentration of net pay across gross interval
RD2070	WELDRN	A_d	acres	well drainage area	5.0 F	minimum of drainage area or well spacing
RD2085	PERHOR	k_h	md	horizontal permeability	10.4 F	indicate source of measure (core, log, DST)
RD2090	PERVRT	k_v	dimensionless	vertical permeability	4.2 F	$k_v:k_h$
RD2120	POROST	ϕ	fraction	total porosity	6.4 F	bulk porosity, including fracture porosity
RD2140	WATSAT	S_{wl}	fraction	initial water saturation	6.4 F	indicate source and whether total liquids
RD2160	PRESIN	P_i	psia	initial reservoir pressure	7.1 F	indicate gradient or measured
RD2170	GASGRV	γ	air=1.0	specific gravity of dry gas	6.4 F	indicate source
RD2180	BHTEMP	T	°F	bottomhole temperature	3 I	correct from logs as needed
RD2200	HEATVL	H	btus/scf	heating value	5.0 F	default from gravity, composition data
RD2210	CO2	CO ₂	fraction	CO ₂ concentration	6.4 F	
RD2220	N2	N ₂	fraction	N ₂ concentration	6.4 F	
RD2230	H2S	H ₂ S	fraction	H ₂ S concentration	6.4 F	
RD2250	WELRAD	r_w	feet	wellbore radius	5.3 F	0.354 in (except slimhole, cavity completion)
RD2290	CHLCON	none	ppm	Cl concentration of produced water	7 I	default at regional average, depositional type
RD2330	FRACSP	L_f	feet	natural fracture spacing	6.2 F	default for lithology
RD2490	PERTYP	none	code	permeability type	1 I	matrix, fracture, or total
RD2500	FRACW	none	inches	natural fracture width	5.3 F	core or history match
RD2510	PORTYP	none	code	porosity type	1 I	matrix, fracture, or total
RD2520	H2ORST	none	ohm-meter	water resistivity	5.2 F	
RD2530	TEMRST	none	°F	temperature of resist. measurement	3 I	
RD3000	DISCYR	none	year	date of reservoir discovery	4 I	

Table 4 - GSAM Resource Data Format (Continued)

Variable ID	Variable Name	Symbol	Units	Description	Format	Notes
RD3010	DISCME	none	code	discovery method	1 I	establish codes
RD3020	SGDVYR	none	year	date of significant development start	4 I	active drilling and production
RD3030	DOMOPR	none	code	dominant operator code 1992	3 I	1 = independents; 2 = integrated; 3 = other
RD3040	WLSPAC	none	acres/well	well spacing (current field rule)	8.1 F	per state proration records
RD3050	ACPROV	none	acres	maximum proved area	8.1 F	indicate actual or derived from wells*spacing
RD3060	ACPRVD	none	year	date of proved area estimate	4 I	
RD3070	ACDV92	none	acres	reservoir developed area EOY 1992	6 I	or date used for history match
RD3100	CGPR92	Q	Bcf	cumulative gas prod. EOY 1992	7.3 F	
RD3110	GRSV92	none	Bcf	proved gas reserves (1992)	4 I	document adjustments to public records
RD3180	GWR92	none	MMcf/bbl	1992 gas-water ratio	7.3 F	trend/avg may be more relevant than 1992
RD3190	PRESC	P _c	psia	current bottomhole shutin pressure	4 I	indicate if WHSIP adjusted to BHP
RD3210	PWFCUR	P _{wf}	psia	bottomhole flowing pressure	7.1 F	tie to production data
RD3230	PRORAT	none	(% of AOF)	regul rate constraint/proration limit	2 I	per state regulation
RD3242	GPRDXX	none	Bcf/yr	82-92 gas production	11 @ 6.1 F	
RD3262	OPRDXX	none	Mbbl/yr	82-92 oil production	11 @ 6.1 F	
RD3282	LPRDXX	none	Mbbl/yr	82-92 NGL production	11 @ 6.1 F	
RD3302	TWELXX	none	#	82-91 total wells	11 @ 6 I	
RD3322	PWELXX	none	#	82-91 producing wells	11 @ 6 I	
RD3342	STWL92	none	#	82-91 shutin wells	11 @ 6 I	
RD3380	PRSGTH	P _{sys}	psia	gathering system pressure	4 I	regional average or per reservoir type
RD3390	PZSLOPE	none	psia/MMcf	P/Z slope	4 I	to be used as calibration of reservoir model

Typical undiscovered reservoirs are defined for each field size class in each geological play, adding the equivalent of another 5,000 reservoirs to be evaluated. A prospect-play resource appraisal technique will be used to generate undiscovered resource field size distributions from play-specific distributions of known fields once validated reservoir level data are available.

GSAM makes two additional changes in gas resource base characterization that will improve the ability to evaluate issues such as reserve growth on a common basis. First, all reservoirs will be converted to a resource-in-place, similar to that done for oil. The lack of volumetric reservoir data for gas reservoirs has precluded this characterization in the past. This more realistically accommodates resource accumulation theory and eliminates the implicit technology and economic factors that affect recovery and size classification. With greater consistency, it should be easier to separate the economic, technology and drilling components of reserve growth.

Second, GSAM will lower the smallest field size class included in its undiscovered resource base. Many producing reservoirs have ultimate recoveries less than the 6 Bcf cutoff used by USGS in its 1989 national assessment. As technology improves, this lower limit size class could decrease. The estimated volume of the undiscovered nonassociated gas resource base used in GSAM will be reconciled with recent USGS estimates and extended to account for economically producible reservoirs as small as 1 Bcf (recoverable).

2. Reservoir Performance

The need to evaluate technology and operating conditions dictates the level of reservoir modeling detail required. GSAM uses a suite of dimensionless pressure type curves to estimate rate and ultimate recovery. The type curve method is grounded in accepted engineering theory and balances the need for explicit technology modeling with the limitations of available reservoir data.

These curves were designed to evaluate the unique production mechanisms found in all significant nonassociated gas resources. Separate type curves were developed for various flow regimes (radial and linear), porosity types (single and dual), drive mechanisms (expansion, diffusion/desorption and water) and phases (one or two) (Table 5).

GSAM has developed enhanced type curves that model a flow unit instead of a single closed boundary well. These type curves evaluate well-to-well interference, providing the ability to evaluate the

Table 5
GSAM Reservoir Performance Models

Module	Reservoir Type	Drive - Mechanism	Flow Geometry	Porosity Type	Number of Fluids	Current Status
I	Conventional Tight	Fluid Expansion	Radial Flow	Single ϕ	Single Fluid* (Gas)	Testing
II	Horizontal well Induced fracture	Fluid Expansion	Linear Flow	Single ϕ	Single Fluid (Gas)	Testing
III	Conventional	Fluid Expansion	Radial Flow	Dual ϕ	Single Fluid (Gas)	Testing
IV	Horizontal well Induced fracture	Fluid Expansion	Linear Flow	Dual ϕ	Single Fluid (Gas)	Testing
V	Conventional	Water-Drive	Radial Flow	Single ϕ	Two Fluids (Gas & Water)	Development
VI	Coal/Shale	Diffusion/ Desorption	Radial Flow	Dual ϕ	1 or 2 Fluids Gas or Water/Gas)	Development
VII	Hydrates	Dissociation	Linear Flow	Single ϕ	Two Fluids (Gas & Water) Plus Hydrate	Phase II
*Geopressed aquifers are analyzed using Module I, except the mobile phase is water.						

potential of up to two infill episodes. They accommodate changing skin, drainage area and flowing pressure over the well life to represent performance degradation (e.g., perforation plugging, proppant embedment) or production practices (e.g., compression, liquids removal). Production is allocated to each well according to production allocation or proration rules specific to each field. At the user's option, the type curves may be run at several levels of detail that allow for faster processing time with a minimum loss of accuracy.

3. Technology Performance

The core analytical feature of GSAM is the ability to represent technologies explicitly. Rather than ambiguously representing technology advances as "increased recovery," GSAM characterizes technologies in terms of the physical or cost parameters that affect the underlying gas flow equations in the reservoir model or costing algorithms in the economics model.

It is inappropriate for a systems model to evaluate individual technologies (e.g., packers types, specific proppants, tubing, drill bits). GSAM is intended to provide insights and general guidance for

R&D planning, leaving decisions about specific projects and priorities to METC R&D managers themselves. Therefore, GSAM represents technologies as groups of hardware or processes with a common impact on both reservoir or cost performance and that would be a common focus of R&D. GSAM defines five major categories of technology:

- Exploration
- Reservoir Characterization
- Drilling
- Completion
- Production

Within these categories are 16 subcategories (e.g., Drilling is divided into structures, equipment, fluids and orientation). The GSAM user specifies technology performance parameters for each subcategory for each resource type to be evaluated. Parameters are derived from field studies of existing technology effectiveness or detailed technology process simulations. The basic gas flow equation below and Table 5 provide examples of the parameters that might be used to represent changes in technologies or operator practices.

$$q = \frac{0.703 \text{ } kh \text{ } (P_c^2 - P_{wf}^2)}{T \mu z \left[\ln \frac{(r_e)}{(r_w)} - 0.75 + s + D_{qs} \right]}$$

Table 6
How GSAM Models Technology Performance

Technology Performance Parameters	Example Technologies Represented by Parameter
h (net pay)	Formation evaluation, multiple completions, horizontal well
P _{wf} (flowing pressure)	Production practices, compression
r _e (drainage radius)	Well spacing, infill drilling
r _w (wellbore radius)	Slimhole drilling, cavity completions
s (skin)	Formation damage, completion/ stimulation, effects, condensate blockage, well placement
D _{qs} (rate dependent skin)	Wellbore configuration, completion design, production practices

4. Reservoir Development

Operators decide how to develop a reservoir based on geologic characteristics, available technology and current gas markets. GSAM models each of these factors. Reservoirs are delineated to some traditional spacing to minimize interference. A plateau production rate is established that optimizes reservoir economics from the initial wells and accommodate field or state rules.

When deliverability can no longer be maintained, the producer evaluates additional development options. Options include:

- Deplete initial wells
- Recomplete/stimulate initial wells
- Infill (one or more times)

Valuable information obtained from initial development about the distribution of reservoir properties creates the potential to high-grade additional development. To model this, GSAM separately evaluates additional development for "pay grades" of different reservoir quality. This feature represents the benefits of R&D to improve the accuracy of reservoir diagnostics and geological modeling.

In addition to available technology, costs and markets, additional development decisions are also influenced by the stage of reservoir depletion. GSAM evaluates the technical performance and costs of more than 50 additional development scenarios for each reservoir. Table 7 shows development options evaluated.

5. Economic Evaluation

Detailed technology evaluation requires corresponding detail in costing. GSAM costs each characterized technology at the AFE level to determine whether its marginal contribution to reservoir performance justifies its marginal cost. Costs are derived from published sources and supplemented by vendor quotes. A discounted cash flow model is used to fully evaluate projects on an industry standard basis (i.e., pro forma project analysis, including state-specific and federal taxes and any incentives).

Table 7
Reservoir Development Options Evaluated By GSAM

Technology Path*		Current-Current		Current-Advanced		Advanced-Advanced	
Development Window**		Open	Close	Open	Close	Open	Close
Pay Grade	Development Option						
1	Recomplete						
1	Infill						
1	Recomplete plus infill						
2	Recomplete						
2	Infill						
2	Recomplete plus infill						
3	Recomplete						
3	Infill						
3	Recomplete plus infill						

* Technology Path incorporates the variation in additional development potential as a function of the relative efficiency of previously applied technologies (i.e., more infill potential exists if primary development was relatively inefficient)

** Development window indicates earliest time (initially assumed at plateau break) and latest time (economic limit of initial wells) an operator would recomplete or infill.

6. Exploration

GSAM models exploration based on expected value of discoveries for drilling in a play or group of plays. Because it is based on extension of past trends, the traditional discovery process method (originally developed by Arps and enhanced by Kaufman and others) is inappropriate to quantify the effects of specific exploration technologies.

GSAM is developing an alternative exploration evaluation method that estimates discoveries as a function of the interaction of geological character of the remaining resource base and the resolution and accuracy of the survey or seismic technology being evaluated in GSAM. Some systems models increase the "artifact" of improved technology (e.g., lower dry hole rates) without accounting for the efficiency limits of the technology. This method, largely made possible by GSAM's detailed play- and size class-

specific reservoir characterizations, will make it possible to estimate how long a technology improvement is likely to increase finding or success rates in a given play. Further development and calibration have been deferred until Phase II, when more detailed reservoir and exploration data are available.

7. Decision Making

GSAM makes investment and production decisions the same way operators do, by evaluating the current and prospective market economics on a risk-adjusted basis. Projects whose marginal economics justify continued or increased investment are pursued, unprofitable ones are terminated. This approach removes a major limitation of traditional supply models, many of which assume that, once a project starts, it is continued regardless of changes in markets. Decision-making is in three areas:

- **Exploration.** Prospects are ranked on a fully-risked, full-cost basis through a play-prospect method. Exploration activity is constrained by infrastructure capacity and the rate at which rigs can be built and moved. A discovery process method is used in Phase I to characterize exploratory drilling and success rates.
- **Reservoir Development.** Discovered reservoirs are evaluated on a sunk exploration cost basis. Development options are evaluated in the context of current markets, technology performance, and stage of reservoir depletion. Multi year reservoir drilling decisions are reviewed and optimized annually on an economic basis.
- **Production.** Production decisions are guided by reservoir deliverability and market constraints. Production may be curtailed if marginal operating cost exceeds revenue or insufficient transport capacity exists. Reservoirs are abandoned as required by law or the economics of bringing them back on production.

These decisions are based on expected wellhead gas prices. GSAM includes the ability to alter the accuracy of price foresight of operators. For example, prices could be assumed to be constant based on current year prices or they could include some expected future trends (e.g., company price forecast).

8. Uncertainty and Risk

GSAM was designed to assess the costs/benefits of alternative R&D programs, evaluate cost/benefits of existing programs, direct/prioritize/scope R&D activities, estimate potential U.S. gas supplies and their market implications and perform analyses of the impact of alternative policies and proposals on domestic gas markets. As such, it incorporates risk analysis methods to treat uncertainty in data and technology performance prediction. Uncertainties are tied explicitly to individual technologies

to assess the risks specific R&D projects METC or industry could undertake. This provides the ability to evaluate R&D potential for projects with different likelihood of technical or commercial success.

There are inherent uncertainties in both resource description and extraction technology performance. In some cases, uncertainty reduction may influence operator decision-making and increase gas recovery more than technology efficiency improvements. GSAM has been structured to address all types of uncertainty through one of several statistical techniques. Uncertainties that GSAM can evaluate include those outside of the scope of DOE's R&D program (e.g., weather, oil prices). These are important because, although not under DOE control, they have major implications for the effectiveness of its R&D program success. Other types of uncertainty (e.g., technology process performance, resource characterization, information transfer) can be reduced by directed METC R&D efforts. Evaluation of uncertainty will be a major focus of Phase II.

9. Other Gas Supplies

Other natural gas supplies are estimated at several levels of detail:

- Associated-Dissolved Gas production is derived exogenously from DOE's Tertiary Oil Information System (TORIS) and the Crude Oil Policy Model (COPM), using technology, macroeconomic and cost assumptions comparable to those used in GSAM. Phase II efforts will provide more integrated estimation of nonassociated and A/D gas.
- LNG is estimated in Phase I as the gradual increase in throughput at existing terminals until current capacity is reached.
- Canadian and Frontier resources will be evaluated by the same reservoir method as for the Lower-48, contingent on the availability of detailed reservoir and resource data.

10. Technology Transfer

Advanced technologies must make it into the marketplace to affect gas production or costs. Regardless of its technical merits, a technology R&D project should receive a low priority if market conditions, competing technologies or costs are likely to prevent its commercialization. GSAM characterizes technology commercialization in terms of initial availability, rate of penetration and market saturation. METC R&D can affect each of these factors, and GSAM can estimate the ability of specific technology transfer strategies to increase technology commercialization (Figure 3).

Figure 3
Market Penetration of Improved Technology

GSAM tracks the use of each technology by region, resource and over time. This provides the key data to determine whether a technology is likely to be a commercial success, regardless of its technical efficiency. The Upstream Module provides a common analytic framework to evaluate the benefits and costs of applying specific technologies to the resource base and marketplace expected to exist in the future.

C. Downstream Module

Design work on the Downstream Module during the period of performance involved adapting the ICF Resources North American Gas Market Model, considered to include all the required capabilities needed in GSAM to evaluate demand, transportation and distribution.

The Downstream Module estimates gas and alternative fuel demand, storage and distribution capacities and costs and adds transportation capacity as needed. These estimates are made at a more aggregate level than for the Upstream Module. Downstream natural gas issues are currently a secondary focus of GSAM, but their impact on gas supplies and supply R&D could be significant. For example, the imposition of a carbon tax or emissions trading strategy would dramatically alter the volume and location of needed gas supplies. Widespread commercialization of gas cooling would alter seasonal gas demand, affecting storage needs.

The value of an integrated gas systems model also benefits downstream R&D planning, including that pursued by METC. Fundamental understanding of the volumes and uncertainties of future domestic gas supplies provides the necessary context to evaluate effectiveness of downstream policies and technologies.

1. Demand

Gas demand is modeled by end-use sector (e.g., residential, commercial, electric utility and industrial) for each of 14 demand regions. Transportation (e.g., natural gas vehicles) will be added as a fifth sector in Phase II.

Existing models and databases of gas demand and its drivers are incorporated into the Downstream Module. Models developed by the Electric Power Research Institute, EIA and ICF Resources are used to parameterize demand (e.g., boiler fuel demand). These models have been widely critiqued and were adapted with minimal enhancements for Phase I.

Because of the importance of future gas demand for electric power generation, GSAM explicitly models gas-powered utility generation. Other sectors are generally modeled as parameterized representations of more detailed ICF Resources or publicly available end-use models (e.g., industrial boiler demand). GSAM addresses interfuel competition and the impact of changes in "exogenous" factors such as weather, GNP, population growth and electricity demand.

2. Transmission and Storage

A detailed representation of the nation's gas transportation system is essential to estimate volumes and costs of future gas flows. GSAM models gas transmission from 26 supply regions and 14 demand regions, resulting in 71 transport links, each of which is characterized by directional capacity, costs and a sophisticated tariff structure (Figure 4).

GSAM endogenously evaluates and builds new pipeline capacity if it is the least-cost alternative to storage, interruption, supplemental peaking or customer-initiated fuel substitution.

Figure 4
GSAM Transmission System

3. Distribution and Seasonality

Distribution costs represent a significant portion of overall delivered gas costs, thereby affecting purchaser decisionmaking. Since gas demand is highly seasonal, GSAM provides a disaggregated representation of seasonality, storage and distribution.

Load duration curves have been developed from current market studies and proprietary in-house utility planning models. GSAM evaluates the least cost method to supply demand from pipeline, customer storage, propane, LNG or interruption.

D. Integrating Module

The Integrating Module balances regional demand, transport capacity and interfuel competition to maximize consumer and producer surplus. It sets the capital and drilling infrastructure constraints that drive exploration and reservoir development decisions.

Integration is implemented through a linear programming optimization that equilibrates regional supply and demand on net gas prices. The model estimates the marginal value of supply to allocate capital and infrastructure. Based on a preliminary price path, the GSAM Upstream Module generates a

40-year schedule of exploration, development and production. Drilling, technology use, resource categories and investments, among other parameters, are tracked by region and over time. Based on the characteristics of the rig fleet and current returns to capital, GSAM retires and adds to drilling infrastructure, thereby explicitly evaluating full and variable drilling costs.

A similar process is used for the Downstream Module. Demand at the assumed prices may or may not match available gas supply. The two time-dependent supply and demand curves are compared by region to generate a new suite of regional price paths and the process is repeated until the price paths converge. With a reasonable initial price basis, this convergence is quite rapid, usually occurring within 3-4 iterations (Figure 5). More detailed description of this process is provided in the GSAM Design Report.

Figure 5
GSAM Logic Flow

VI. Results and Discussion

A. Results Achieved During Period of Performance

GSAM's highly disaggregated resource and technology characterization allows it to assess alternative federal natural gas R&D, tax, regulatory and environmental policy initiatives at a previously available level of detail. It will also be available to industry to support capacity planning and market analysis for various end users and provide comprehensive gas industry environmental impact assessments,

ICF Resources has developed a working prototype of GSAM and is now calibrating the model and data. We reviewed relevant natural gas upstream, downstream and market models to identify appropriate analytic capabilities to incorporate into GSAM. We also reviewed commercial gas extraction technologies to better characterize performance and costs in terms of GSAM parameters.

We have developed databases for the gas resource base, engineering costs, exploration, pipeline capacity and volumes, alternative gas sources and gas utilization. Although an accurate reservoir-level resource database is not yet available, we have generated a synthetic reservoir-level database that broadly reflects the geological characteristics and volumes by region, depth and resource type. This database is being used to provide limited model testing and validation.

GSAM operates on a DOS platform and currently runs on a 486DX2/66 machine with 16 Mb of RAM and a 250 MB hard disk. The hardware requirements of GSAM will be reevaluated as part of the Peer Review to determine any model changes are desirable. User manuals will be developed early in Phase II and a priority given to improving run time efficiency.

B. Research Difficulties and Methods Developed to Overcome These Difficulties

GSAM cannot be validated, calibrated, peer reviewed or used for DOE R&D planning or policy, however, until it has access to the validated reservoir level data for which it was designed. The core concept of GSAM was to build a modeling system that integrated geology, technology, economics and

markets. That capability is grounded in the ability to define the unique interactions between reservoir properties and explicit technologies on a disaggregated level. This capability addresses one of the most serious limitations of natural gas modeling that even the NPC couldn't overcome - the need for reservoir level resource data.

We have temporarily circumvented this obstacle by redirecting some budget and effort to developing a synthetic resource base. This resource base is volumetrically consistent with published resource estimates and provides GSAM with a database at the level of typical reservoirs (i.e., each reservoir is described in terms of explicit reservoir properties). Although these data are being used to continue development of the model, GSAM cannot undergo a Peer Review to conclude Phase I until such data are provided.

C. Planned Research For the Next Reporting Period

The principal focus of the next reporting period (June 22, 1993 to June 21, 1994) is the completion of the GSAM prototype and Peer Review. Based on that review, modifications will be made and GSAM will be made available to METC for resource appraisals, technology assessments and policy analyses.

Appendix A - Research Work Breakdown Structure

Research activities were conducted during the reporting period in the following areas:

1 REVIEW TECHNOLOGIES

- 1.1 Establish technology selection criteria
- 1.2 Finalize technologies to evaluate with METC
- 1.3 Collect data on current technology applications and R&D in progress (lit search)
- 1.4 Contact operators and researchers for additional data
- 1.5 Tabulate technology performance data and map application locations
- 1.6 Characterize technologies as to SOA, limitations, potential, and set selection guidelines
- 1.7 Prepare topical report and brief METC personnel on technology review
- 1.8 Revise technology reviews and report as needed

2 REVIEW MODELS

- 2.1 Establish model evaluation criteria/objectives
- 2.2 Conduct METC review of models to be reviewed and evaluation criteria
- 2.3 Gather models/documentation/applications data
- 2.4 Evaluate models
- 2.5 Prepare topical report/briefing to METC personnel on models
- 2.6 Revise model reviews and report as needed

3 DEVELOP METHODOLOGY

- 3.1 Inventory and evaluate resource data by resource category
- 3.2 Evaluate model and data compatibility/usefulness
- 3.3 Refine GSAM concept
- 3.4 Finalize GSAM analysis/data requirements
- 3.5 Revise proposed approach and work plan as needed
- 3.6 Submit final development plan in topical report and briefing
- 3.7 Revise concept and/or plan as needed

4 DEVELOP MODELS

- 4.1 Supply Models
 - 4.1.1 Resource data
 - 4.1.2 Create reduced form reservoir models
 - 4.1.3 Create reduced form technology models
 - 4.1.4 Create engineering and costing models
 - 4.1.5 Incorporate uncertainty in supply models
 - 4.1.6 Validate models and set standards for integration (iterate as needed)
 - 4.1.7 Document reduced form models, data and validation results
 - 4.1.8 Peer review component supply models and data
 - 4.1.9 Revise supply data/models per peer review

- 4.2 Demand Models
 - 4.2.1 Demand data
 - 4.2.2 Create reduced form demand models
 - 4.2.3 Create engineering and costing models
 - 4.2.4 Incorporate uncertainty in demand models
 - 4.2.5 Validate models and set standards for integration (iterate as needed)
 - 4.2.6 Document reduced form models, data and validation results
 - 4.2.7 Peer review component demand models and data
 - 4.2.8 Revise demand data/models per peer review
- 4.3 Market Models
 - 4.3.1 Collect market /integration model data
 - 4.3.2 Develop market/integration model components
 - 4.3.3 Develop standards for supply/demand component linkage
 - 4.3.4 Incorporate uncertainty in market model
 - 4.3.5 Validate market model components and set standards for integration(iterate as needed)
 - 4.3.6 Document market model capabilities, data and validation results
 - 4.3.7 Peer review market model
 - 4.3.8 Revise market model per peer review
- 4.4 System Integration
 - 4.4.1 Integrate model components
 - 4.4.2 Prepare GSAM benchmark runs
 - 4.4.3 Develop GSAM testing and validation plan
 - 4.4.4 Document integrated model capabilities and limitations
- 5 TEST AND VALIDATE
 - 5.1 System validation
 - 5.1.1 Test against boundary conditions
 - 5.1.2 Compare to literature/other broad models/Industrial forecasts
 - 5.1.3 Test adequacy of uncertainty treatment
 - 5.1.4 Validate adequacy of datasets
 - 5.2 Integrated system peer review
 - 5.2.1 Overall model
 - 5.2.2 Components in context of integrated model
 - 5.2.3 Reconciliation of component reviews
 - 5.2.4 Recommendations and priorities for further model development
 - 5.3 Document validation and peer review process
 - 5.4 Correct models/data as needed
 - 5.5 Prepare plan for Phase II model/data enhancements per peer review
 - 5.6 Prepare User's Guide, code description, datasets
 - 5.7 Submit testing and validation topical report and briefing

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