UNIVERSIDAD DE CARABOBO

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ESCUELA DE INGENIERÍA MECÁNICA

Evaluación de la factibilidad del incremento de eficiencia de la generadora de vapor y su subsistema de generación que permitan la optimización de la potencia en la unidad número 1 de la Central Termoeléctrica de Planta Centro CADAFE.

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C.I: 18.108.347

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Trabajo especial de grado presentado ante la Ilustre Universidad de Carabobo para optar al título de Ingeniero Mecánico

Tutor académico:
Prof. *Ing. Nilo Espinoza*
Tutor externo:
Ing. Oscar Villarroel

Autores:
Sergio Morales
C.I: 18.108.347

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Quienes suscriben, Miembros del Jurado designado por el Consejo de Escuela de Ingeniería Mecánica para examinar la Tesis de Pregrado titulada *"**Evaluación de la factibilidad del incremento de eficiencia de la generadora de vapor y su subsistema de generación que permitan la optimización de la potencia en la unidad número 1 de la Central Termoeléctrica de Planta Centro CADAFE.**"*, presentada por el bachiller: Sergio Morales, portador de la Cédula de Identidad Nº: **18.108.347**, respectivamente; hacemos constar que hemos revisado y aprobado el mencionado trabajo.

_____

Prof. Tutor, *Ing. Nilo Espinoza*
Presidente del jurado

_____

Prof. Jurado1, *Ing. Aquiles Vera*
Miembro del jurado

_____

Prof. Jurado2, *Ing. Grúber Caraballo*
Miembro del jurado

En Naguanagua a los 23 días del mes de noviembre de 2011

Agradecimientos

Quiero expresar, sin tomar en consideración un orden específico, mi más sincero agradecimiento a mi tutor, el Profesor ....., por sus consejos, guiatura y sugerencias oportunas durante el desarrollo de este trabajo de investigación. De igual manera agradezco a los Profesores ..... y ....., quienes en todo momento, durante el desarrollo de la investigación, estuvieron atentos y prestaron toda colaboración, orientación, guiatura y dirección académica para la realización de .....

Resumen

En este trabajo se presenta una solución eficiente de problemas ..... para la detección de cavidades usando una técnica de ..... empleando el método de elementos de los elementos finitos. La superposición de un conjunto de cargas puntuales para simular la presencia de cavidades ofrece una ventaja en la reducción del tiempo computacional en problemas de elastostática; el uso del método de elementos de contorno optimiza el proceso ya que no se requiere re-discretizar el dominio.....

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Introducción

El objetivo principal de la generación de vapor es producir vapor a una presión mayor a la atmosférica, de manera de aprovechar la energía que posee en tales condiciones y cubrir las necesidades de la empresa.

El calor necesario para evaporar el agua proviene de la energía liberada en el proceso de oxidación de un combustible. Dicha liberación de energía se manifiesta en forma de calor (calor de combustión) y se transfiere al agua por mecanismos de radiación, convección y conducción.

La importancia de conocer la eficiencia térmica con que operan los generadores de vapor, también denominados calderas, radica en evaluar el grado de aprovechamiento de la energía del combustible para producir vapor.

Además, se pueden cuantificar las cantidades de calor que ingresan y egresan de una caldera.

El diagnóstico de la operación de un sistema energético consiste en descubrir e interpretar los signos de un mal funcionamiento de los equipos que lo componen y cuantificar sus efectos en términos de consumo adicional de recursos; es decir, saber dónde, cómo y qué parte del consumo global de recursos puede ser ahorrado, manteniendo constantes la cantidad y especificaciones de los productos del sistema, así como los condicionantes externos que afectando a su comportamiento no pueden ser manipulados por el operador.

El diagnóstico de los sistemas energéticos forma parte de las estrategias de mantenimiento correctivo. Una vez que se conoce, a través del diagnóstico, el mal comportamiento de ciertos equipos y su efecto individualizado sobre el consumo adicional de recursos del sistema con relación a una referencia, cabe aprovechar esta información para mejorar la operación tomando las acciones correctivas pertinentes. En el caso de las centrales termoeléctricas el mal funcionamiento de ciertos equipos como las calderas comienza a tener un gran impacto económico incluso para pequeñas desviaciones de su comportamiento con respecto al esperado por diseño. Por ello deben buscarse unos resultados del diagnóstico que tengan la máxima certidumbre compatible con la cantidad y calidad de medidas disponibles. También resulta deseable que el diagnóstico sea en tiempo real para facilitar el mantenimiento rápido de la central tras detectar los primeros síntomas de degradación del comportamiento de los equipos. En definitiva, un buen sistema de diagnóstico debería aprovechar toda la instrumentación disponible en planta y en todo momento.

Los procedimientos normativos, como por ejemplo las ASME Perfomance Test Codes 4.1 fueron concebidos, sobre todo, como test de aceptación de los equipos, y son fuentes de información muy útiles para diseñar los procedimientos de diagnóstico en tiempo real

de los sistemas energéticos. Pero padecen de dos inconvenientes serios: uno es la rigidez en el tratamiento de la información, que puede ser superado utilizando técnicas de reconciliación de datos; y otro su carácter aislado y local (equipo a equipo) que impide un análisis directo del efecto de la degradación del comportamiento de los equipos en el conjunto del sistema (ASME, 1993). Para superar esta limitación se han propuesto en años recientes distintos métodos de diagnóstico que se han aplicado tanto en centrales termoeléctricas convencionales como a centrales de ciclo combinado con turbina de gas. Entre ellos se encuentran los métodos de diagnóstico termoeconómico que utilizan el concepto de coste exergético, para valorar el consumo de combustible debido a las irreversibilidades locales.

CAPITULO I

1.1 Aspectos generales de la empresa

A continuación se presentan unos tópicos generales, que brinda información de la ubicación, y propósito de la empresa donde se desarrollo el proyecto del cual nace el trabajo de tesis.

1.1.1 Reseña Histórica

La historia de la electrificación en Venezuela inicia cuando se instaló en Maracaibo el primer sistema regular de alumbrado público un año después valencia pasa a ser la segunda ciudad en disfrutar de este tipo de servicio.

Para 1946 la corporación venezolana de fomento el sistema eléctrico venezolano se encontraba fragmentado, evidenciando la necesidad de emprender de inmediato un estudio a fondo de las posibilidades y potencialidades del sector, CADAFE compañía anónima de administración de fomento eléctrico, fundado el 27 de octubre de 1958 como la unión de 15 pequeñas empresas, adquiridas por el gobierno nacional a través de la corporación venezolana de fomento, como una solución a la necesidad de contar con un servicio eléctrico a escala nacional que sirviera de soporte al crecimiento del país.

En 1964 se inicia en Venezuela la construcción de Planta Centro la mayor planta termoeléctrica de América latina, con una capacidad proyectada de 4000 MW, en 1978 inicia su operación comercial, cuya construcción se desarrollo en 2 fases de las cuales la primera colocó en funcionamiento la unidad 1 con una capacidad instalada de 400 MW, en 1979 se duplicó la capacidad de la planta con la puesta en marcha de la unidad numero 2, ambas construidas bajo la contratación, llave en mano, KRAFTWGRK UNION (KWU), empresa que fabrico en sistema de turbina y generadores y la compañía BORSIG del grupo Alemán BABCOCK que se encargó de la fabricación de las caldera, el desarrollo de las unidades 3,4 y5 se realizó en la segunda fase cada una con la misma capacidad de instalación que las anteriores, pero se construyeron basándose en un proyecto multicontrato con un aporte de la ingeniería venezolana en septiembre de 1981 se inició la unidad numero 3simultaneamente con unidad 4 iniciando sus operaciones comerciales en 1989, actualmente planta centro posee una capacidad instalada de 2000 MW que representa el 50% de su capacidad proyectada.

Ocupa un área de 207 hectáreas, ubicada en punta morón estado Carabobo, para su construcción se realizó un estudio detallado sobre su efecto sobre el medio ambiente, para conseguir un mínimo de distorsión ambiental, la planta termoeléctrica planta centro es una de las mayores realizaciones llevada a cabo por el gobierno nacional, siendo su función principal la producción de energía eléctrica para el suministro de energía continuo y confiable para el desarrollo social e industrial del país y el desarrollo integral de todo nuestro territorio.

1.1.2 Ubicación de la empresa.

La compañía anónima de administración de fomento eléctrico CADAFE, Planta Centro está ubicada en punta morón carretera nacional morón estado Carabobo litoral central de Venezuela.

1.1.3 Misión.

Prestar un servicio eléctrico integral eficiente, de calidad técnicamente confiable, a precios que nos permitan cubrir los costos operativos y efectuar las inversiones requerida para el mantenimiento, mejoramiento y aplicación rentable del sistema, estimulando el desarrollo del país y con ella la calidad de vida de la población.

1.1.4 Visión.

Ser una empresa de carácter corporativa, no burocrática, organizada funcionalmente para prestar un servicio eléctrico integral eficiente de calidad comparable a las mejores empresas del sector eléctrico tanto nacional como internacional con tecnología eficiente.

1.1.5 Objetivos de la empresa.

1. Producir energía eléctrica en condiciones seguras, confiable a bajos costos con personal motivado y productivo dentro de un clima de trabajo sao a través del sistema de generación y distribución de electricidad, garantizando en suministro de forma permanente a través de una extensa red que abarca el oriente, occidente y sur del país.

2. Satisfacer la demanda de energía eléctrica, de toda la estructura productiva industrial y los requerimientos del desarrollo urbano y rural, manteniendo disponible el 75% de la capacidad efectiva instalada.
3. Mantener la disponibilidad de energía necesaria, para cada unidad.
4. Proporcionar un clima laboral sano en condiciones óptimas con el personal motivado y productivo en un sistema de generación y distribución eléctrica.
5. Establecer beneficios socioeconómicos para satisfacción de las necesidades del trabajador.

1.2 Planteamiento del problema:

En la actualidad, las compañías de generación y distribución de energía eléctrica se ven sometidas a grandes presiones para dar una mejor calidad en el suministro, lo que les exige poner en marcha proyectos de investigación y desarrollo encaminados a implantar tecnologías y métodos de explotación que solventen las deficiencias en la continuidad del suministro de energía.

Venezuela es un país que cuenta con grandes cantidades de recursos, derivados del petróleo, como Fuel Oíl y gas natural, los cuales son utilizados como combustible por centrales termoeléctricas como Planta Centro CADAFE, para aprovechar la energía calorífica y transformarla en energía mecánica, que posteriormente se trasforma en electricidad; **Ver figura 1.1** Planta Centro ubicada en la zona costera de Morón, municipio Juan José Mora estado Carabobo, tiene una capacidad instalada de generación de 2000MW, a través de 5 turbinas a vapor con la capacidad de generar 400 MW cada una, estas trabajan bajo la modalidad del ciclo Rankine regenerativo con recalentamiento intermedio; la energía producida en Planta Centro, es aportada al Sistema Interconectado Nacional (SIN), a través de las subestaciones El Isiro (Estado Falcón), Cabudare (Estado Lara) y La Arenosa (Estado Carabobo).

En cuanto al uso de la energía eléctrica, Venezuela se encuentra actualmente en el primer puesto de América Latina con 4.126 kWh per cápita, por delante de Chile, Argentina, Uruguay y Brasil.

Por lo tanto la demanda de generación de energía eléctrica va en aumento, por lo que se tiene que garantizar el suministro y la cobertura de energía eléctrica, principalmente en el área rural a corto plazo.

Actualmente el complejo, termoeléctrico Planta Centro CADAFE no está generando su capacidad instalada, las 5 unidades que la conforman están en un estado no eficiente, presentando numerosas fallas que impiden su plena producción y que con el correr del tiempo estas se incrementan.

Hoy día las unidades, operativas son la 1,2 y 3 generando un promedio de 300 MW cada una, tal situación de las citadas unidades, ocasionan un déficit de energía

eléctrica en la zona central del país, por tal razón la empresa CADAFE se ve en la necesidad de realizar una revisión mayor a la unidad número 2 que se llevará a mediados del próximo año, para recuperar la capacidad instalada de la misma.

Siguiendo este orden de ideas, la unidad número 1 es la menos eficiente, de todas las unidades operativas, además ya que sobrepasó holgadamente, el lapso de las 50.000 horas, equivalentes de servicio, lapso recomendado por el fabricante.

Después de todo lo expuesto, es imperativo tomar acciones que contribuyan de manera concreta, al incremento de generación de energía en las unidades de la central Termoeléctrica, mediante un estudio de ingeniería, que solo se realizará en la generadora de vapor y sus subsistema de generación de la unidad número 1, con la finalidad de recuperar la potencia perdida de esta unidad, y así cumplir con todas las exigencias energéticas, demandadas de la industria y de la población de la región central del país.

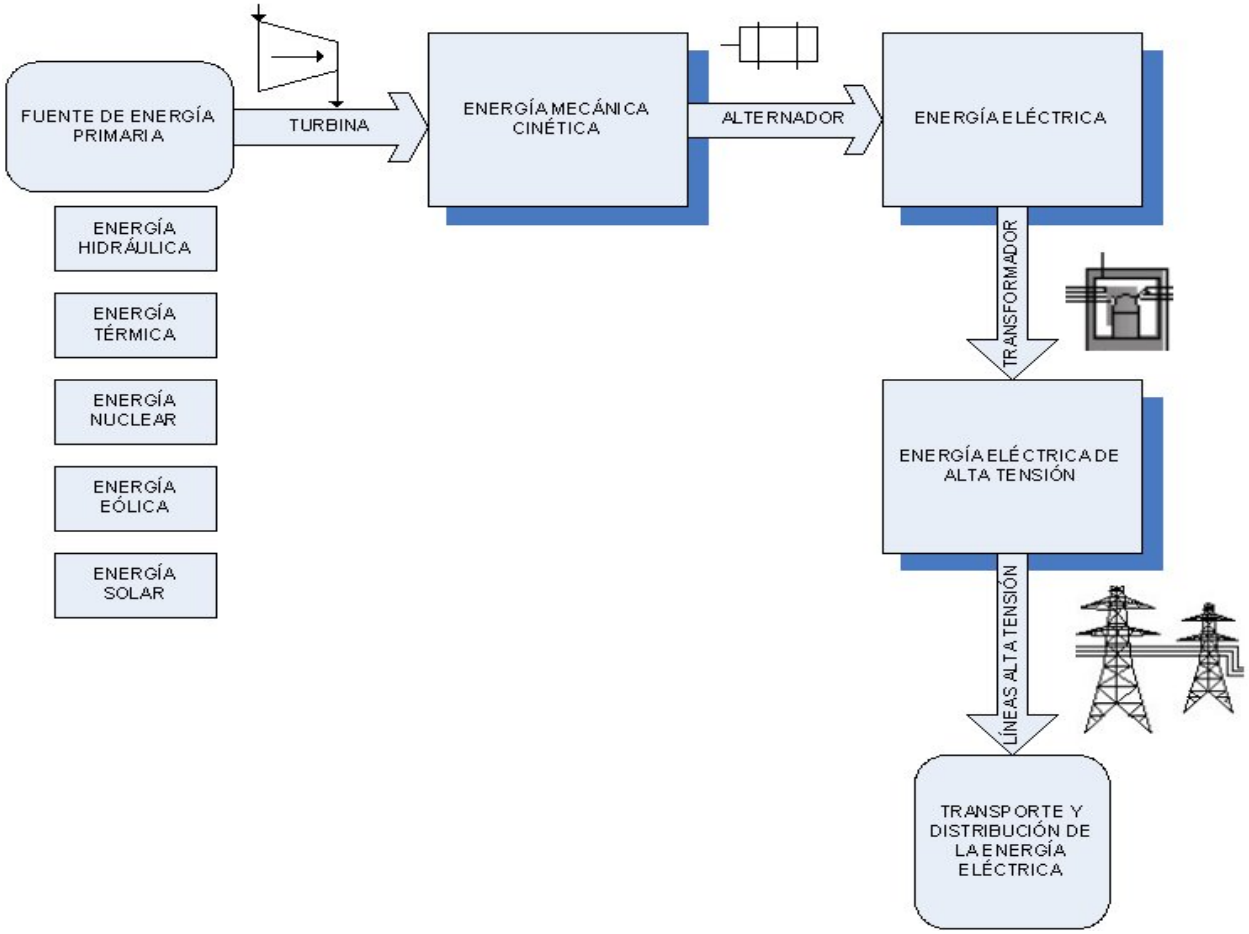

Figura 1.1: Esquema de Generación eléctrica.

1.3 Justificación

La empresa CADAFE comprometida con la producción, distribución de energía eléctrica de toda la región central de Venezuela, se ve en la necesidad de implementar un plan de recuperación para todo el complejo termoeléctrico Planta Centro, con la finalidad de identificar y solucionar, todas las fallas y así poder recuperar su capacidad instalada, iniciándose con un estudio integral, de la unidad número 1 de dicho complejo energético.

1. Este estudio pretende dejar una serie de beneficios para la empresa CADAFE, como son recuperación de la potencia generada en la unidad número 1.
2. Identificación y solución de los problemas más críticos existentes en la unidad generadora de vapor y sus subsistemas de la unidad número 1.
3. Con este estudio se pretende, presupuestar todas las mejoras a realizarse y así poder, destinar el presupuesto necesario, para llevarlas a cabo, además de adelantar todos los trámites administrativos respectivos.
4. Este estudio servirá de modelo, para futuros análisis de las demás unidades de generación de vapor, que conforman la central termoeléctrica Planta Centro.
5. Con el perfeccionamiento de la unidad número 1, se optimizan las condiciones, del sistema interconectado, y con ello la población, de toda la región central de Venezuela gozará de un mejor servicio eléctrico, reduciéndose las fallas en sistema.
6. Además la Universidad de Carabobo, obtendrá una serie de información útil, ya que se está trabajando con temas, de suma importancia para la ingeniería mecánica, como lo es el caso de una unidad generadora de vapor, de la empresa CADAFE, del complejo Planta Centro.
7. Por último el autor obtendrá una serie de conocimientos, en el área de suma importancia, para la carrera de manera práctica ya que está es una empresa donde se pone en ejecución, muchas tareas de ingeniería.

1.4 Objetivo General del Trabajo:

Evaluar la factibilidad del incremento de eficiencia de la generadora de vapor y su subsistema de generación que permitan la optimización de la potencia en la unidad número 1 de la Central Termoeléctrica de Planta Centro CADAFE.

1.5 Objetivos Específicos:

1. Analizar cómo se está generando el vapor en la Caldera de la Unidad número 1 y las condiciones de funcionamiento de sus componentes
2. Identificar los factores que influyen en la generación de vapor.
3. Establecer una relación entre los resultados obtenidos de la investigación y la problemática que presenta la unidad número 1.
4. Proponer soluciones a los problemas existentes en la unidad generadora de vapor de la unidad número 1.

1.6 Alcance:

- Se pretende identificación y presentar propuestas para la solución de los problemas más críticos existentes en la unidad generadora de vapor y sus subsistemas de la unidad número 1.
- Este estudio servirá de modelo, para futuros análisis de las demás unidades de generación de vapor, que conforman la central termoeléctrica Planta Centro.

1.7 Limitaciones:

- Tiempo establecido por la empresa para desarrollar la investigación.
- La información que hasta ahora se mantiene en alta confidencialidad, debido a las políticas de la empresa.

CAPITULO II

2.1 Antecedentes preliminares:

El estudio de la eficiencia de una caldera permite, obtener información de cómo están trabajando los componentes, que conforman dicho equipo, permitiendo realizar un diagnostico antes de que se presente alguna falla.

En los últimos años, la investigación se ha centrado en el logro de avances tecnológicos para mejorar e incrementar la eficiencia de las calderas, cuyos hallazgos más relevantes se citan seguidamente.

Remiro et al., en el año 2007 presentaron como el diagnóstico termoeconómico ayuda al ingeniero a detectar las anomalías de funcionamiento que disminuyen la eficiencia de una central termoeléctrica, e identificar los equipos en que se producen y a estimar su impacto en consumo adicional de combustible según dos métodos complementarios.

Cada uno de estos métodos determina el impacto de combustible debido al mal funcionamiento de los equipos. Los métodos se aplican al diagnóstico de la operación de una central y se analiza la calidad de los resultados tomando en consideración las incertidumbres de los datos.

Golato et al., en el año 2008 desarrollaron un método matemático determinístico de procesamiento de registros experimentales, aplicable a un sistema generador de vapor-precalentador de aire en estado estacionario, que opere con uno o dos combustibles simultáneamente, para determinar la eficiencia térmica del mismo y la eficiencia con la que se oxida el combustible, como así también el rendimiento del intercambiador de calor. La mecánica de procesamiento se basa en la resolución de los balances de materia y energía sobre los diferentes equipos que conforman el sistema.

Eoff et al., en el año 2008 midieron la eficiencia de una caldera de vapor y demostró que la reducción de la temperatura de los humos de la chimenea aumenta la

eficiencia, ya que por cada 40 ºC que baje la temperatura de los humos de la caldera conseguimos un incremento en la eficiencia de un 1 %. Un economizador típico puede incrementar la eficiencia de la caldera en un 4 – 6 %.

En el año 2009 se han realizados estudios para mejorar la calidad de los materiales con que se fabrican los componentes de las calderas, Hisham et al., presentaron un estudio de nuevas resinas como alternativa a los componentes metálicos de las calderas; en las calderas de condensación colgadas en pared y para uso residencial, las resinas Noryl, Ultem y Cycoloy pueden reemplazar los metales tradicionales como cobre y latón usados en los componentes de la caldera, incluyendo carcasas del condensador y conectores. En calderas de condensación de alta eficiencia, las resinas Noryl PPX ofrecen una ventaja sobre las carcasas de los condensadores de acero inoxidable por su resistencia química y capacidad para resistir el calor requerido desde el condensador. Los accesorios de la caldera se fabrican tradicionalmente de tubos de cobre y piezas de latón, pero actualizando a estas resinas puede permitir a los fabricantes disminuir el número de piezas, reducir el peso, y ahorrar en costes de fabricación y ensamblaje.

En este mismo orden de ideas, Frederic A. Hooper, Jr. y Ronald D. Gillette. En el año 2010 realizaron un programa que modela un sistema de distribución de vapor, calcula un valor para la eficiencia del sistema y permite calibrar el modelo. También calcula el coste ideal del sistema, divide los dos números, y da el porcentaje resultante. Esto representa exactamente el sistema de distribución de vapor.

En el año 2010, Stephen Hall. Jack Lyons, demostraron que cuando el hogar de una caldera envejece, aparecen pérdidas de aire en los pequeños huecos que se forman entre las penetraciones del tubo, envolvente, aperturas del soplador de hollín, puertas de observación, y los espacios de aire muertos comienzan a contribuir al aire total suministrado al hogar. Sin embargo, cuando ocurren pérdidas entre la salida del hogar y la salida de la caldera, el aire no contribuye al aire total requerido para una apropiada combustión. Simplemente se diluye el caudal de gas y artificialmente se eleva la indicación de oxígeno en exceso.

2.2 Fundamentación teórica

Cuando se busca en un diccionario el significado de la palabra caldera, entre las diversas acepciones que aparecen, se encuentran: recipiente metálico, grande y más o menos redondeado y cilíndrico que sirve para hervir un líquido y generar vapor que será empleado para producir energía o como sistema de calefacción. Viendo esta definición, ya se puede saber en qué radica su importancia en la industria, que en definitiva es el lo que se va a estudiar; una caldera es el punto de partida en la producción de energía en la inmensa mayoría de las empresas.

Una caldera es un intercambiador de calor; transforma la energía química del combustible en energía calorífica. Además, intercambia este calor con un fluido, generalmente agua, que se transforma en vapor de agua. En una caldera se produce la combustión que es la liberación del calor del combustible y la captación del calor liberado por el fluido. **Ver figura 2.1**

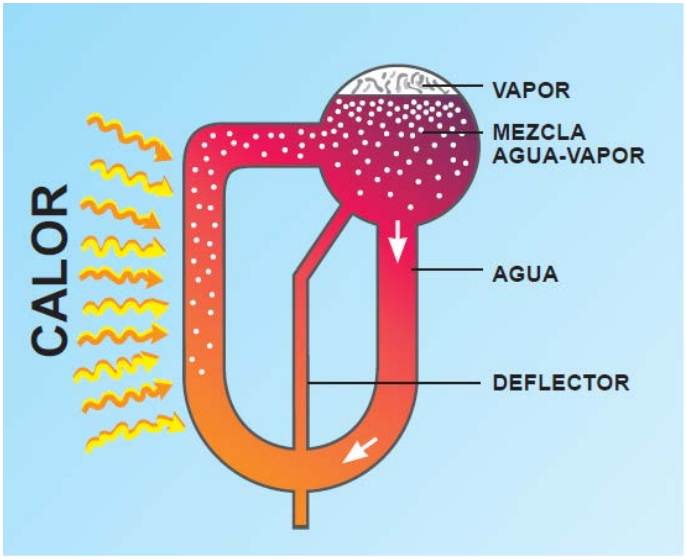

Figura 2.1 *Cambio de fase del agua bajo la acción del calor.*

La caldera es necesaria para poder realizar la gran mayoría de los trabajos y a su vez, también para el confort de las personas ya que gracias a ella las personas reciben calor en todos los lugares que posean una caldera. Este calor recibido de la caldera viene dado por los mecanismos básicos de transmisión de calor: la conducción es el calor que pasa de una parte a la otra de la pared del hogar, o de los tubos de humos; la convección,

los tubos de humos se calientan al contacto con los productos de combustión y, por último, la radiación se produce un intercambio de calor de la llama, a las paredes del hogar.

Hasta principios del siglo XIX se usaron calderas para teñir ropas, producir vapor para limpieza, etc., hasta que Papín creó una pequeña caldera llamada “marmita”. Se usó vapor para intentar mover la primera máquina homónima, la cual no funcionaba durante mucho tiempo ya que utilizaba vapor húmedo (de baja temperatura) y al calentarse ésta dejaba de producir trabajo útil. Luego de otras experiencias, James Watt completó una máquina de vapor de funcionamiento continuo, que usó en su propia fábrica, ya que era un inglés muy conocido. La máquina elemental de vapor fue inventada por Dionisio Papín en 1769 y desarrollada posteriormente por James Watt en 1776. Inicialmente fueron empleadas como máquinas para accionar bombas de agua, de cilindros verticales. Ella fue la impulsora de la revolución industrial.

Máquinas de vapor alternativas de variada construcción han sido usadas durante muchos años como agente motor, pero han ido perdiendo gradualmente terreno frente a las turbinas. Entre sus desventajas encontramos la baja velocidad y (como consecuencia directa) el mayor peso por KW de potencia, necesidad de un mayor espacio para su instalación e inadaptabilidad para usar vapor a alta temperatura. A lo largo de la historia se han construido calderas para tracción, utilizadas en locomotoras para trenes tanto de carga como de pasajeros; una caldera multihumotubular con haz de tubos amovibles, preparada para quemar carbón o lignito. Para medir la potencia de la caldera, y como dato anecdótico, Watt recurrió a medir la potencia promedio de muchos caballos, y obtuvo unos 33.000 libras-pie / minuto o sea 550 libras-pie/seg., valor que denominó ‘Horse Power’, potencia de un caballo. Posteriormente, al transferirlo al sistema métrico de unidades, daba algo más de 76 kgm/seg.

Pero, la Oficina Internacional de Pesos y Medidas de París, resolvió redondear ese valor a 75 más fácil de simplificar, llamándolo “Caballo Vapor” en homenaje a Watt.

2.3 Partes de una caldera

Una caldera está compuesta principalmente de:

- Hogar o cámara de combustión, en el cual tiene lugar la combustión del combustible, su forma y tamaño depende del tipo de combustible.
- Un cuerpo intercambiador en el que se absorbe parte del calor liberado en la combustión. Es la zona donde se encuentra el agua; forma la caldera.
- Una envolvente que aísla térmicamente el hogar y el cuerpo intercambiado.
- Hogar holandés es el hogar suplementario exterior a la propia disposición de la caldera y usado para aumentar el volumen del hogar.

Para apreciar mejor las partes de una caldera **Ver figura 2.2**

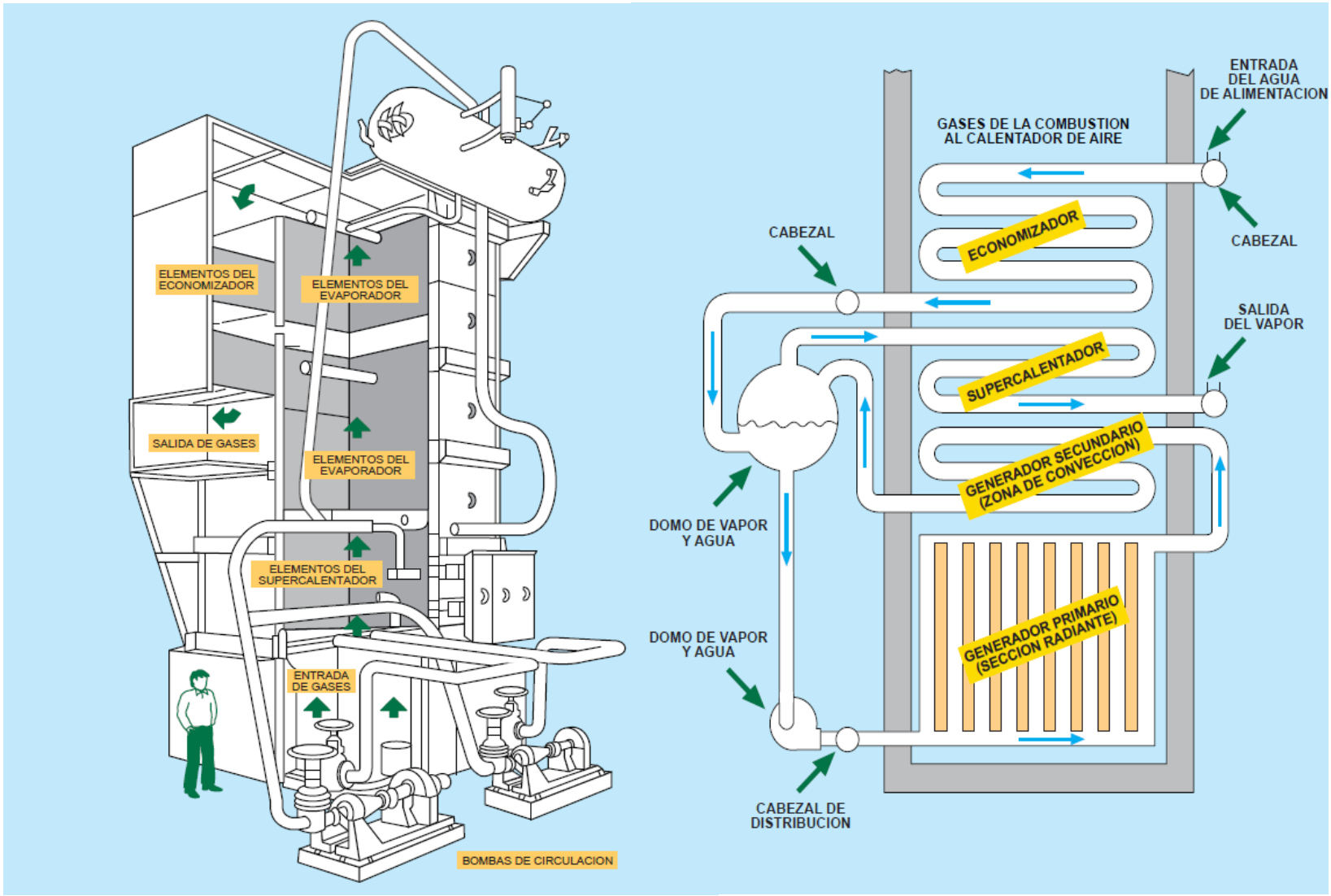

Figura 2.2 *Elementos que conforman una caldera.*

2.4 Tipos de calderas

Las calderas se pueden clasificar en:

- De acuerdo a su posición
  - Vertical.
  - Horizontal
- de tubos de agua o acuotubulares:
  - Calderas de acero:
    - ✓ de hogar en depresión.
    - ✓ de hogar presurizado.
  - de tubos de agua y humos.
- de tubos de humo o pirotubulares.
  - Calderas de fundición.

2.4.1 Calderas de tubos de agua o acuotubulares:

En las calderas acuotubulares, el agua circula por dentro de tubos, en vez de alrededor de ellos (pirotubulares), pasando los gases calientes alrededor de los tubos. Estos tubos están situados en el exterior del calderin de vapor.

Las ventajas de este tipo de calderas son:

- Puede obtenerse mayor capacidad aumentando el número de tubos, independientemente del diámetro del calderin de vapor.
- El calderin está expuesto al calor radiante de la llama.
- La mayor ventaja es la libertad de incrementar las capacidades y presiones.

Este tipo de caldera facilitan el montaje de la misma, da mayor de calidad en fabricación y es más económico.

2.4.2 Calderas acuotubulares compactas:

Este tipo de calderas pueden quemar todo tipo de combustible variando las características del hogar y los equipos de combustión y posee una serie de ventajas:

- Al instalar múltiples unidades en lugar de una sola caldera grande, el calentamiento se basa en la carga por caldera, suministrando una gran elasticidad durante los periodos de demanda baja de vapor.
- Los pequeños generadores de vapor pueden colocarse cerca de la carga de vapor evitando pérdidas y reduciendo el tamaño.
- La capacidad de reserva puede suministrarse con un sistema de calderas múltiples.

Dentro de estas calderas se diferencian dos tipos, de hogar integral pequeñas que se utilizan cuando se requiere una rápida instalación y se dispone de poco espacio o puede ser necesario el traslado de la caldera; y de hogar integral grandes las cuales se utilizan para la producción de vapor de energía y cuando los problemas de espacio obliguen al aprovechamiento de este.

2.4.3 Calderas acuotubulares no compactas:

Estas calderas son montadas en obra y constan de una parte de tubos y tambores con sus conexiones y la otra de mampostería en ladrillo refractario. Estas pueden ser de tubos rectos o de tubos curvados, los cuales son más flexibles que los rectos; y permiten una mayor superficie de calefacción.

2.4.4 Calderas acuotubulares de alta presión y alta temperatura:

Estas calderas poseen multitud de ventajas como las siguientes:

- Gran capacidad de almacenaje térmico.
- Ausencia de calor en la línea de retorno.
- No se necesitan purgadores, bombas de condensado, depósitos, de esa forma, el coste primario es menor, menor mantenimiento y ausencia de pérdidas de vapor.
- No es necesario un sistema caro de tratamiento de agua.

- Calderas tienen ladrillo refractario; estos ladrillos pueden variar en sus características:
- Conductividad térmica a diversas temperaturas.
- Densidad.
- Difusividad térmica.
- Calor específico, que condiciona la cantidad de calor almacenado en el material.
- Emisividad que regula a la cantidad de calor radia o absorbida por las paredes, techo y suelo.

2.4.5 Caldera de chapa de acero:

Este tipo de calderas son diseñadas para todo tipo de potencias y presiones de trabajo. Pueden ser de alta o de baja presión y hoy en día son de construcción soldada.

2.4.6 Calderas de tubos de humos:

La caldera de humos o Pirotubular, es decir, tubos de fuego, es aquella que necesita transferencia térmica para que se pueda extraer del combustible y del material la mayor parte del calor que las condiciones económicas permitan. El flujo de los gases de la combustión se realiza por el interior de los tubos; los gases de combustión que salen del hogar pasan previamente por el interior de un haz de tubos que se encuentra en el cuerpo de la caldera bañados por el agua con el fin de aumentar la superficie de calentamiento de la misma, antes de ser expulsado por la chimenea.

2.4.7 Calderas de fundición:

Las calderas de fundición son unidades de calefacción de baja presión construidas por secciones de fundición a presión de acero, bronce o latón. Los tipos normales fabricados son clasificados por el modo en que se ensamblan las secciones de fundición por medio de conectores o niples, conectores exteriores y maguitos roscados.

Hay tres tipos de calderas de fundición:

- **Calderas circulares de fundición:**

Es un conjunto atornillado donde el combustible se quema en el hogar central, con los gases subiendo y fluyendo a través de diversos pasos de las secciones llenas de agua y finalmente salen por la chimenea.

- **Calderas verticales de bloques:**

Son secciones ensambladas frontales con trasera, y en posición vertical, atornilladas o unidas por medio de conectores roscados.

- **Calderas por secciones horizontales:**

Este tipo de calderas se utiliza normalmente con gas y un quemador para cada caldera o sección vertical múltiple.

2.5 Calderas pirotubulares para combustibles líquidos o gaseosos:

Dentro de este tipo de calderas pirotubulares existen diferentes tipos, como de hogar integral en la cual se obtiene una llama alargada por la parte baja del hogar; también puede ser compacta con tubo de hogar, la cual está formada por un tubo central sumergido en el agua, el cual hace de hogar; en este caso la transmisión de calor se realiza por radiación; el rendimiento de este tipo de calderas alcanza hasta un 90%.

Las calderas pirotubulares tienen una serie de ventajas que son las siguientes:

- Bajo coste
- Bajo mantenimiento
- Capacidad de soportar fluctuaciones de carga grandes y bruscas, y variaciones de presión
- Simplicidad de instalación

A pesar de las ventajas que presentan las calderas pirotubulares también tienen algunas desventajas, tales como:

- La limitación del tamaño por la resistencia de la carcasa
- Tensiones térmicas
- Peligro de explosión
- Difícil mantenimiento

2.6 Selección del tipo de caldera:

Lo primero es tomar en cuenta a que tipos de trabajo será sometida la caldera. Luego se debe tener el conocimiento de las cualidades que debe tener para ser empleadas en las diversas funciones.

Entre los diversos datos debemos conocer:

- La Potencia de la Caldera
- El Voltaje que esta Requiere
- El Tipo de Combustible que esta Necesita para Trabajar
- La Demanda de Vapor que se Requiere, etc.

Se puede decir que en realidad existen varios factores importantes al momento de elegir una caldera, tales como:

- Capacidad de Consumo de la Empresa
- Capacidad de la Caldera
- Capacidad de Turbina / Generador

La selección del tipo de caldera más adecuado y económicamente eficiente para una instalación industrial se hace más fácil cuanto menos cueste el combustible y la mano de obra y menor número de tipos de calderas de confianza y los regímenes normales a elegir. Lo que habrá que tener en cuenta es si la elección de tipo de caldera cilíndrica o de otra construcción dará resultado económico.

El rendimiento térmico influye en el gasto de combustible, pero no es lo más importante para la economización de la caldera, pudiera ser que una caldera de elevado rendimiento térmico, sea poco rentable por sus costos de mantenimiento y funcionamiento.

La cantidad de malos resultados obtenidos con gran número de unidades reducidas no se deben a defectos de construcción como al uso del combustible inadecuado, a falta de tiro o al mal funcionamiento. Esto nos puede pasar con cualquier tipo de caldera, y solo se puede solucionar con personal especializado y con la mejora de instrumentos y aparatos de los que se espera unos resultados más económicos.

El coste inicial es factor decisivo, esto resulta una equivocación, puesto que un reducido aumento del coste inicial puede ser recuperado en los primeros diez meses.

Los factores que intervienen en la elección de una caldera son:

- Combustible y tiro
- Agua de alimentación
- Presión, potencia evaporadora
- Funcionamiento y mantenimiento.

2.7 Condiciones que debe cumplir una caldera:

1. Incorporación de materiales apropiados, una mano de obra cualificada y un cumplimiento de las Reglas de Fabricación Idóneas.

2. Debe tener un colector de lodos e impurezas colocado de tal manera que pueda ser manipulado fuera de la acción del fuego.

3. Capacidad de agua y vapor suficientes para prevenir las fluctuaciones del vapor y del nivel de agua.

4. Una superficie suficientemente grande para el desprendimiento del vapor de agua para evitar los arrastres de agua.

5. Una constante circulación de agua en el interior para mantener la temperatura uniforme en todas sus partes.

6. Buenas condiciones de dilatabilidad de las distintas partes de la caldera para evitar tensiones inadecuadas que provocarían la rotura del aparato. La caldera debe haber sido diseñada de tal forma que si se produce rotura no halla explosión.

7. Alta resistencia.

8. Una cámara de combustión tal que la combustión se inicie y finalice dentro del hogar.

9. Unas superficies de calefacción colocadas de tal manera que permitan extraer el máximo contenido del calor de los gases.

10. Todas las partes de la caldera deben ser accesibles para poder limpiarlas y repararlas fácilmente.

11. Dependiendo de nuestras necesidades elegiremos una u otra caldera.

12. Nunca deben faltar los aparatos de medición, válvulas de seguridad.

2.8 Construcción de una Caldera.

Es una costumbre generalizada valorar las calderas por la superficie de calefacción total que disponen, considerando que a mayor superficie de calefacción, la caldera será mejor en relación a otra de superficie inferior.

Un análisis profundo de una caldera debe comportar los siguientes aspectos:

- Diseño de la caldera en sus aspectos de facilidades de inspección, mantenimiento y eventuales reparaciones.
- Diseño de la caldera en relación a la absorción de las dilataciones diferenciales que se producen entre sus partes.
- Sistema de unión tubo/placa y en especial en la placa tubular de la cámara trasera de hogar.
- Tipo de unión placas/envolvente.

- Dimensionado del hogar, comprobando los valores de carga y densidad específica en relación a las indicaciones de TA-LUFT y Normas DIN de dimensiones de llama:
- Carga específica <= 1,5 Mw/m3 = 1.290.000 Kcal/m3
- Densidad específica <= 7.200.000 Kcal/m2 (sección circular del tubo hogar)
- Diámetro hogar >= 0,17*Qi1/3,5
- Longitud hogar >= 0,2*Qi1/2 / siendo Qi el calor introducido en Kcal/h.
- Temperatura de los gases al final del hogar y a la entrada del primer haz tubular.
- Nº de tubos, tamaño y longitud del primer haz tubular.
- Nº de tubos, tamaño y longitud del segundo haz tubular.
- Temperatura gases al final del primer haz tubular y a la salida de la caldera.
- Velocidad de los gases en las diversas partes de la caldera.
- Pérdida de carga del circuito de gases.
- Espesores de las distintas partes del cuerpo a presión y calidad de los materiales empleados.
- Volúmenes de la cámara de agua y vapor, así como, superficie de evaporación (plano de agua)
- Sistema separador de vapor.
- Tipos de controles y seguridades.
- Marca de todos los accesorios, equipos y válvulas instalados en la caldera.
- Tipo de equipo de combustión. Producción mínima garantizada.

Como se puede ver, el valor de la superficie total de la caldera no aparece en el análisis anterior y como mucho se tiene el análisis de las distintas superficies de calefacción que componen la caldera y que tienen un comportamiento diferente.

Se indicaran unos valores medios orientativos de los flujos caloríficos a través de las distintas partes de una caldera:

Según sea la importancia relativa de una superficie frente a otra, el valor medio variará, de forma que si se aumenta la superficie de los haces tubulares y en especial el segundo, el valor medio de Kg/m^2 total de la caldera bajará, sin que ello quiera decir que se mejoran las prestaciones de la caldera.

En los primeros diseños de este tipo de calderas pirotubulares, de hogar interior, cámara húmeda y tres pasos, alrededor del inicio de los años sesenta se diseñaban con vaporizaciones medias de 25 Kg/m^2 con hogares sobredimensionados y gran número de tubos y gran diámetro, ofreciéndose al mercado "calderones" en comparación con las dimensiones actuales de calderas de igual producción. A medida de que los incrementos de coste de los materiales y en especial de la mano de obra fueron siendo más importantes, se tuvieron que diseñar calderas con tasas medias de vaporización superiores, reduciendo significativamente la superficie de calefacción por convección (haces tubulares) que da las tasas de transferencia de calor más pequeñas, por medio de menor número de tubos y en ciertos casos de menor diámetro, además de ajustar las dimensiones del hogar a los valores límites según Normativa, en función de la potencia nominal de la caldera.

Esta evolución en el diseño fue tan espectacular que se alcanzaron diseños con tasas medias de evaporación de 60 Kg/m^2 que comportaban unas pérdidas de carga elevadas en el circuito de gases. Actualmente los principales fabricantes europeos de este tipo de calderas, con producciones anuales de más de 3000 unidades, diseñan sus calderas bajo los siguientes patrones:

- Temperatura máxima de entrada de los gases al primer haz tubular de 1000 ºC
- Rendimiento (sin economizador) : 89,5 o 90%
- Pérdida de carga en el circuito de gases: 40 a 120 mm. H_2O (variable, incrementándose con el tamaño de la caldera).

Estas condiciones dan como resultado unas tasas medias del orden de 45 a 55 Kg/m^2, sin que este valor sea indicativo de nada más.

Finalmente, otro mito existente en el mercado de las calderas es que el precio de venta de una caldera debe ser proporcional a su superficie de calefacción.

Una variación de un 20% en la superficie de calefacción media de una caldera, afectará principalmente a los tubos y en una reducción de mano de obra además de una ligera disminución del valor de las chapas del cuerpo caldera y aislamiento. Estas reducciones afectarían solo al 49,31% pues los accesorios, bombas quemador y cuadro eléctrico permanecen invariables. Esta reducción como máximo podría alcanzar un 4% del

valor total de la caldera y dado que un 50% del precio de la caldera depende del equipo instalado en la caldera podría darse el caso de que calderas con menor superficie de calefacción fuesen del mismo precio que otras de mas superficie, debido a las eventuales diferencias de calidad y por ende de precio entre estos accesorios.

Así pues, valorar en su justa medida la relación calidad/precio de las diversas calderas existentes en el mercado, conlleva un estudio en profundidad de los equipos que afectan prácticamente al 50% del precio y que normalmente son los causantes de los problemas que pueden aparecer durante el servicio de la caldera, tales como, quemador, válvulas de cierre y seguridad, elementos de control, etc.

- ✓ Determinar la potencia térmica real necesaria en cada instalación y seleccionar una caldera que no exceda de la potencia calculada:

La tendencia habitual a la hora de diseñar y calcular una central térmica es sobredimensionar los generadores, para absorber cualquier error de cálculo y garantizar la potencia instantánea necesaria en los momentos de máxima demanda. Aquí entra el famoso 10% de inercia (según unos) o de intermitencia de servicio (según otros), que se añade a la potencia calculada, por poner un ejemplo generalizado, ya que existen otros incrementos “gratuitos’ a gusto de cada proyectista o instalador.

Los efectos negativos que conlleva a instalación de generadores sobredimensionados, son múltiples, pero no es momento de relacionarlos todos, nos centrará en los que afectan al consumo, o mejor dicho, al rendimiento estacional. La práctica totalidad de las instalaciones de potencias medias y altas, así como buena parte de las de pequeñas potencia, utilizan generadores presurizados o semigresurirados (las definiciones a gusto de cada uno), a los que se acoplan quemadores mecánicos con soplante. Esto es así refiriéndonos a combustibles gaseosos, ya que existen calderas dotadas de quemadores atmosf6ricos, utilizadas generalmente para potencias pequeñas. En el caso de combustibles líquidos, no haremos distinciones entre potencias, porque todos los generadores incorporan quemadores con soplante, por la necesidad de la pulverizaci6n del combustible por presi6n.

Refiriéndonos a este tipo de generadores compuestos por caldera y quemador con soplante, deberemos tener en consideración la obligatoriedad de efectuar un prebarrido de la cámara de combustión, consistente en la introducción de aire a temperatura ambiente de la central térmicas (salvo excepciones puntuales), durante un período de tiempo variable y directamente proporcional a la potencia del generador, en el interior del hogar de la caldera.

Pues bien, parece que nadie se ha detenido a considerar las pérdidas de calor que supone la introducción de aire a una temperatura de 20 °C durante un minuto (por ejemplo), en una caldera con una temperatura media de agua de 70 °C. En sí, un prebarrido sería insignificante pero a mayor número de prebarridos, el efecto de cada uno se suma, consiguiéndose determinar con exactitud el valor de las pérdidas totales, por indeterminación de la integración en el tiempo de las pérdidas instantáneas.

La determinación de las pérdidas instantáneas o pérdidas por cada prebarrido, se podrían calcular como producto entre el calor especifico del aire, el caudal de aire introducido y el salto térmico entre la entrada y salida por el conducto de humos del mismo. Esto que parece tan sencillo, supone un problema, ya que disponemos de dos constantes y dos variables, una de ellas de difícil determinación a priori, ya que la temperatura de salida del aire de la caldera, será directamente proporcional a la temperatura del hogar y a las características constructivas del mismo (superficie de contacto). Aún así, se podría determinar una temperatura media que nos diera un valor aproximado pérdidas en cada prebarrido, por cada tipo de generador, en función de la temperatura ambiente de la central térmica.

Ahora viene la segunda parte, la integración. Para determinarlas pérdidas totales en un periodo de un día (por ejemplo) sería necesario conocer el número de prebarridos que un generador realiza en dicho espacio de tiempo y eso es imposible de determinar, ya que las instalaciones de calefacción están sujetas en su funcionamiento a las evoluciones de a temperatura ambiente exterior, por lo que variará el número de prebarridos, con las condiciones de funcionamiento de la instalación, en función de la demanda instantánea, que a su vez se rige por la diferencia entre la temperatura ambiente interior consignada y la temperatura exterior.

2.9 Combustión

Se define la combustión como una reacción química rápida exotérmica en la que se realiza la oxidación de una sustancia y la reducción de otra. Las temperaturas de combustión oscilan entre 1000 ºC y 1650 ºC.

Para que se produzca la combustión es necesario que haya tres elementos fundamentales:

- **Comburente**: es la sustancia que se reduce. El comburente más habitual es el oxígeno contenido en el aire atmosférico.
- **Combustible**: la sustancia que se oxida, es decir, el elemento que se quema. Los más habituales son carbono (C), hidrogeno (H), oxigeno (O) y a veces, nitrógeno (N) y azufre (S).
- **Temperatura de ignición**: debe ser lo suficientemente elevada como para producir el encendido.

2.9.1 Reacciones químicas

Las reacciones químicas deben satisfacer unas condiciones para que tengan lugar en el proceso de combustión:

- Adecuada proporción entre combustible y comburente.
- La mezcla de las dos sustancias debe ser uniforme.
- La temperatura de ignición se establecerá y será monitorizada de manera que el combustible continúe su ignición sin calor externo cuando comience la combustión.

2.9.2 Tipos de combustión

Se pueden dividir en dos apartados:

- ***Según los productos que se obtienen:***

➢ Combustión con exceso de aire

Existe una cantidad de aire superior al mínimo necesario. Cuando se utiliza exceso de aire, no se producen inquemados.

➢ Combustión con defecto de aire

Es la que se lleva a cabo con menor cantidad que el aire mínimo necesario.

Cuando se utiliza combustión con defecto de aire tiende a producirse inquemados.

➢ Combustión completa

Es aquella en la que se emplea un exceso de aire controlado y el combustible se oxida completamente, por lo que todo el carbono se transforma en dióxido de carbono (CO_2), es decir, no se produce monóxido de carbono (CO). Las reacciones fundamentales de combustión son:

$$C + CO_2 \rightarrow CO_2$$

$$H_2 + ½\ O_2 \rightarrow H_2O$$

$$S + SO_2 \rightarrow SO_2$$

Donde:

C: Carbono

CO_2: Dióxido de carbono

S: Azufre

H_2O: Agua

SO_2: Dióxido de azufre

- Combustión incompleta

Es aquella en la que los gases de combustión contienen compuestos parcialmente oxidados (hidrógeno, CO…) y se produce una disminución de la cantidad de calor obtenida. Esta combustión puede ser con exceso o con defecto de aire. De entre los inquemados, el más importante es el CO. Libera menos calor que la completa.

Una parte "a" del carbono del combustible pasa a CO_2 y el resto "1-a" a CO:

$$a. \quad C + a.O2 \rightarrow a.CO_2$$
$$(1 - a). \quad C + (1\text{-}a)/2\ O2 \rightarrow (1 - a).CO$$

2.9.3 Aire de Combustión

Conocida la estequiometria de las reacciones que intervienen en la combustión y considerando que la composición de un kilogramo de combustible es:

C = Kg. de carbono/Kg. de combustible
H = Kg. de hidrógeno/Kg. de combustible
S = Kg. de azufre/Kg. de combustible
O = Kg. de oxígeno/Kg. de combustible
W = Kg. de agua/Kg. de combustible
A = Kg. de ceniza/Kg. de combustible

$$C + H + S + O + W + A = 1$$

Los cálculos para obtener la cantidad de oxígeno necesaria para realizar la combustión completa son:

1 mol C = 12 gr. → 1 mol O_2 = 32 gr.
1 Kg. C → x Kg. O_2

X = 2.67 Kg. O_2

1 mol H_2 = 2 gr. → 1/2 mol O_2 = 16 gr. → X =8 Kg. O_2

1 mol S = 32 gr. → 1 mol O_2 = 32 gr. → X =1 Kg. O_2

Teniendo en cuenta los resultados obtenidos, la cantidad mínima de oxígeno es:

$$Omin = 2.67C + 8H + S - O \ (Kg.O_2/Kg.\ combustible)$$

Pero en la atmósfera no tenemos realmente oxígeno, así que la cantidad de aire que necesaria será:

$Amin = Omin / 0.23 \ (Kg.O_2/Kg.\ combustible)$

$V\ Amin = Amin / 1.293 \ (m^3/Kg.)$

2.9.4 Exceso de aire

El exceso de aire se debe a que el tamaño de las partículas del combustible impide una mezcla perfecta entre el combustible y el comburente y a que el tiempo que permanece la mezcla dentro del hogar es muy corto, saliendo por la chimenea una parte de aire que no ha reaccionado. Al introducir mayor comburente, aparecen reacciones secundarias. Esto obliga a emplear una cantidad real de aire comburente mayor del aire mínimo de combustión; por tanto, el exceso de aire es la diferencia entre el aire realmente introducido y el aire mínimo calculado. La relación entre los dos tipos de aire es el coeficiente de exceso de aire:

$$n = \frac{Areal}{Amin}$$

Se queman las sustancias combustibles del combustible, hasta el máximo grado de oxidación. Esto quiere decir que no tendremos sustancias combustibles en los humos.

Los valores entre los que oscila *n* son:

n = 1.5 – 2.0 para combustibles sólidos.

n = 1.1 - 1.2 para combustibles líquidos.

n = 1.0 - 1.1 para combustibles gaseosos.

Este exceso de aire puede provocar reacciones secundarias con los productos de la reacción y más humos:

$$S\ O_2 + ½\ O_2 \rightarrow SO_3$$

$$SO_3 + H_2O \rightarrow SO_4H_2$$

SO_3: trióxido de azufre

SO_4H_2: ácido sulfúrico

El ácido sulfúrico provoca corrosiones en los conductos y chimeneas cuando se condensa por debajo de 150ºC; si se producen estos ácidos, tendremos que evacuar los humos a temperaturas superiores por la chimenea, con lo que se producen pérdidas de calor importantes (Pérdidas por el calor sensible de los humos).

2.9.5 Composición de los Humos

Teniendo en cuenta las reacciones producidas en la combustión, sabemos que los humos están formados por: CO_2, CO, H_2O, SO_2, N_2, O_2, H_2, CH_4 e hidrocarburos ligeros.

A través de los pesos moleculares, podemos hallar los volúmenes de estos gases producidos en la combustión de 1 Kg. de combustible:

Volumen_CO_2 humos = 22.4 / 12 x. C	(m^3 CO_2 / Kg. combustible)
Volumen_CO humos =22.4 / 12 (1-x) .C	(m^3 CO / Kg combustible)
Volumen_H_2O humos = 22.4 / 2.H + 22.4 / 18.W	(m^3 H_2O/Kg. combustible)
Volume_SO_2 humos = 22.4 / 32.S	(m^3 SO_2/Kg combustible)

Debemos tener en cuenta, que además de los productos de combustión, en los humos también existirá el oxígeno no consumido en la reacción y el total de nitrógeno introducido; así que el volumen de oxígeno en los humos será la diferencia entre el realmente introducido y el consumido en la reacción para la formación de CO_2, CO, H_2O, SO_2:

VO_2 humos = $O_{introducido} - O_{consumido}$ =22.4 [(n-1). (C/12 + H/4 + S/32 – O/32) + (1-x).C/24]

(m^3 O_2/Kg. combustible)

El volumen total de humos (volumen de humos húmedos) será la suma de los volúmenes obtenidos anteriormente:

Volumen_total = VCO_2 + VCO + VH_2O + VSO_2 + VO_2 + VN_2

El volumen de humos secos es el volumen total de humos descontando el volumen ocupado por el vapor de agua formado en la combustión.

2.10 Combustibles

Llamamos combustible a toda sustancia capaz de arder, es decir, aquella que es capaz de combinarse rápidamente con oxígeno con un desprendimiento de calor más o menos interno.

Todos los combustibles industriales se caracterizan por estar constituidos por mezclas de pocos elementos. La mayor proporción en peso está formada por carbono, hidrógeno y en la mayoría de los casos azufre. El resto está constituido por la humedad, cenizas, oxígeno y nitrógeno, y en su presencia origina problemas tecnológicos y de explotación específicos de cada tipo de combustible.

Características de los Combustibles:

- **Poder calorífico:** es la energía por la unidad de masa de combustible que se libera en la combustión completa habiendo lactantes y productos con las condiciones estándar. Esta magnitud tiene carácter de entalpía y puede calcularse en función de los calores liberados en las reacciones.
- **Poder calorífico superior (P.C.S.):** se da cuando el proceso de combustión ha acabado y el vapor de agua que había en los humos se ha condensado. Se mide en un calorímetro.

$$P.C.S. = 8100.\ C + 34400.\ (H - O/8) + 2500.S$$

- **Poder calorífico inferior (P.C.I.):** se mide si al enfriarse los productos de combustión hasta la temperatura inicial, el agua se mantuviese en estado gaseoso.

P.C.I. = 8100. C + 28700. (H – O/8) + 2500. S – 600. W

- **Poder comburívoro:** es la masa de aire necesaria para realizar la combustión estequiometria de un Kg. de combustible.
- **Poder fumígero:** es la masa de humos secos producidos en la combustión estequiometria de un Kg. de combustible.
- **Límites de inflamabilidad (inferior / superior) (Li / Ls):** es el valor mínimo / máximo del porcentaje de combustible en la mezcla para los que se produce la combustión. Si superamos el Ls, la ausencia de comburente impide la combustión. Si no alcanzamos el Li, la falta de combustible no permite la combustión.
- **Temperatura de inflamación:** es la temperatura del combustible para la que se inflaman por primera vez los vapores emitidos por el combustible si se ponen en contacto con una llama. Su valor depende de diferentes factores: estado de división, proporción de la mezcla.
- **Temperatura de combustión:** es la temperatura superior a la de inflamación a la que se produce la combustión de los vapores de un combustible durante 5 ó más segundos cuando se pone en contacto con una llama. Su valor depende del estado de división, proporción de la mezcla, presencia de catalizadores.

2.11 Tipos de Combustible

2.11.1 Combustibles Sólidos

a. Tipos:

- **Madera:**

- Combustible más antiguo y más tradicional.
- No presenta gran interés en la industria.
- Elemento biodegradable aún después de su combustión.
- Precio razonablemente económico (incluso gratis).
- Afecta a varios aspectos sensitivos (olor, vista, tacto, oído).
- Es un elemento combustible sin poder de explosión.

- Alto poder calórico de algunas especies.

➢ **Residuos vegetales:**

- Muy numeroso.
- Consumo limitado a las industrias que lo generan o a zonas concretas.
- Se consumen en hogares diseñados para su combustión.

➢ **Carbón natural:**

Combustible fósil sólido, formado a partir de antiguas plantas que crecieron en pantanos o a lo largo de las costas.

Los tipos de carbón natural son:

➢ **Turbas:**

- Masas fibrosas de materia vegetal parcialmente descompuestas que se
- han acumulado en lugares inundados de agua.
- Se utilizan como combustibles pobres.
- Su potencia calorífica es inferior a los lignitos, hullas y antracitas que
- oscilan entre 30000-15000 KJ/Kg.
- Contenido de carbono: 55-65 %.
- Humedad > 75%.

➢ **Lignitos:**

- Ha sufrido un proceso de carbonización superior a la turba.
- Se dividen en lignitos pardos y lignitos negros.
- Contenido de carbono: 65-75%.
- Humedad: 70%, siendo necesario desecarlo para mejorar la combustión.
- Se consumen en centrales térmicas situadas a bocamina.

- Se da en La Coruña, Teruel, Barcelona, Zaragoza, Lleida y Girona.

➢ **Hullas:**

- Carbones caracterizados por ser tanto portadores de energía como
- materias primas en la industria química y metalúrgica.
- También se les llama carbones de piedra.
- Contenido de carbono: 75-90 %.
- Se da en Asturias, León, Palencia, Burgos, Ciudad Real y Córdoba.
- **Antracita:**
- Carbón más antiguo, duro y denso.
- Contenido de carbono > 90%.
- Humedad escasa.
- Alto contenido de calor.
- Se usa en la metalurgia y en la gasificación fuera de su combustión
- directa.
- Es el mejor combustible de los carbones.
- Se da en Asturias, León, Palencia, Burgos, Ciudad Real, Córdoba, Zaragoza, Lleida y Girona.

➢ **Combustibles sólidos artificiales:**

- Se obtienen al someter a un combustible sólido a la acción del calor sin
- contacto con el aire, o bien, a partir de residuos de petróleo.
- Se queman en casos muy específicos.

➢ **Carbón Vegetal**

La madera es un compuesto de oxígeno, hidrógeno, carbono y nitrógeno. Estas sustancias se transforman en otros a través de la combustión. Si quemamos la madera al

aire libre, hacemos que ésta se consuma por completo; si la quemamos en espacios cerrados que sólo dispongan de unas pequeñas aberturas para dar paso al aire, lograremos que las sustancias que necesitan menos cantidad de oxígeno ardan antes que otras. De esta forma, una vez que paremos la combustión adecuadamente podremos recoger las sustancias de la madera que no han entrado en combustión, las cuales forman lo que llamamos carbón vegetal.

Así que el carbón vegetal no es más que leña que ha sufrido una combustión incompleta. Se trata casi de carbono puro y es preferible al carbón natural.

2.11.2 Combustibles Gaseosos.

a. Tipos:

- **Gas natural:**

- Mezcla de hidrocarburos ligeros.
- Aparece en yacimientos similares a los del petróleo.
- Formado principalmente por metano.
- Al mezclarse con el metano se obtiene etano, propano, butano y otros
- compuestos.
- Las proporciones de cada componente son muy variables.
- El grisú se puede considerar una variante.
- Fácil manejo.
- Gran rendimiento.
- Respuesta rápida.
- Necesidad de poco mantenimiento.
- Poco contaminantes.
- Incoloro e inoloro.
- Se inflama fácilmente.
- No es venenosos pero produce asfixia.

- **Gases licuados del petróleo (G.L.P.):**

- Se obtienen en las operaciones de refino del petróleo.
- El propano se usa en la industria debido a su mayor presión.
- El butano para usos domésticos.

- **Gases residuales del refino del petróleo:**

- Gases obtenidos al separar el butano y el propano que no pueden transformarse económicamente en gasolinas y otros productos.
- Dependiendo del proceso de refino, su composición varía.

2.11.3 Combustibles Líquidos.

a. Tipos:

- **Derivados del petróleo:**

El petróleo bruto o el crudo del petróleo el combustible líquido natural por excelencia, aunque se utiliza como materia prima de la cual se obtienen diferentes derivados del petróleo.

El petróleo se obtiene de los restos de organismos vivos, al ser cubiertos por las aguas o por las tierras, sufren la acción química de las bacterias anaerobias, los efectos de las grandes presiones y temperaturas, dando lugar en su descomposición a hidrocarburos líquidos e hidrocarburos gaseosos.

- **Gasóleos:**

Pertenecen a la categoría de destilados puros, compuestos por una gama de hidrocarburos cuyo número de átomos de carbono está comprendido entre C14 y C20.

- ✓ Suele ser de un color amarillento de olor característico.
- ✓ Su temperatura de ebullición oscila entre 220-390ºC.
- ✓ Se destila en un rango de 360 ºC.

- ✓ Punto de inflamación mínimo: 55º C.
- ✓ Menos denso que el agua.
- ✓ Puede desarrollar electricidad estática por agitación o descarga en recipientes.
- ✓ Reacciona con oxidantes fuertes con riesgo de incendio y explosión.
- ✓ Sus vapores son más densos que el aire pudiendo inflamarse a distancia.
- ✓ Puede afectar al cuerpo humano por absorción cutánea, ingestión o inhalación.

Irrita los ojos, la piel y las vías respiratorias, pues destruye las grasas de la piel.

Una alta concentración puede causar pérdida del conocimiento.

Por su calidad y en función del uso al que se destinan, se clasifican en:

- ✓ Gasóleo A: es el de mejor calidad y más alto precio. Se suele emplear en automoción.
- ✓ Gasóleo B: es de igual calidad que el anterior. Se suele usar en la agricultura. Antes de su venta se caracteriza a través de un aditivito de agentes trazadores y colorante rojo.
- ✓ Gasóleo C: calidad inferior a os anteriores. Se suele usar en los generadores de calor de cualquier potencia térmica. Antes de ser suministrado se le colocan agentes trazadores. Es el más utilizado como fuente de energía en la industria en zonas próximas a los núcleos urbanos.

- ➢ **Fuelóleos:**

Son productos residuales de la destilación del petróleo a más de 350 ºC. Son los residuos pesados de la destilación y forma hidrocarburos entre 25 y 35 carbonos.

Pueden proceder de una única etapa del proceso de refino, aunque se obtiene por mezclas de productos procedentes de distintas partes del proceso. Su punto de inflamación mínimo es de 65 ºC.

Los fuelóleos son sistemas heterogéneos en los que existen: emulsiones de minúsculas burbujas de aire y de distintas gotas de agua.

Impurezas extrañas a los hidrocarburos.

Hidrocarburos en forma sólida o gaseosa emulsionados en la fase líquida.

Son los combustibles más utilizados en la industria y se dividen en:

- Fuelóleo nº 1.
- Fuelóleo nº 2: lo utilizan los grandes consumidores industriales: centrales térmicas y cementeras.

2.12 Monitorización de la eficiencia energética o Rendimiento de la Caldera.

La monitorización del rendimiento de la caldera puede revelar una degradación, que si es detenida y corregida puede incrementar la eficiencia de la misma en direcciones técnicas y financieras, quizás por reducción de costo de combustible.

Se describirán dos (2) métodos para calcular le eficiencia de la caldera para la monitorización del rendimiento basadas en la norma ASME PTC 4.1 **ver anexo D.**

2.12.1 Método Directo.

$$Eficiencia = \frac{Energía\ saliente}{Energía\ Entrante} x100 \qquad \text{E.C 2.1}$$

Es necesario establecer las condiciones de la caldera, para ajustar el punto de consigna de modo que las condiciones puedan hacerse en las mismas condiciones operativas de la caldera.

Este método simplificado de obtener la eficiencia puede usarse para detectar tendencia de rendimiento por comparación de rendimientos previos con resultados normales.

La mejor comparación se obtiene con una lectura de puntos de referencia cuando la caldera es nueva o después de una limpieza y revisión general.

2.12.2 Método Indirecto.

El método indirecto se llama método de las pérdidas y se rige por el código de pruebas ASME PTC 4.1 (**ver anexo D**) de calderas y recipientes a presión, que es un procedimiento para determinar la producción de las calderas grandes, incluyendo los cálculos de balance térmico.

$$\eta_{CALDERA} = \left(1 - \frac{\sum P}{PCI \text{ ó } PCR}\right) * 100 \qquad \text{E.C 2.2}$$

Este método exige medir los gases de combustión y también efectuar un último análisis del combustible, su ventaja es que indica donde están ocurriendo las pérdidas, haciendo así posible aumentar la eficiencia, si las pérdidas identificadas pueden reducirse.

La desventaja, muchos datos y cálculos.

CAPITULO III

3.1 Marco metodológico

Para el desarrollo de este proyecto de optimización, de la generación de potencia en la unidad número 1, de la Central Termoeléctrica de Planta Centro, CADAFE fue necesario realizar una serie pasos y procedimientos, que ayudaron a determinar los diferentes inconvenientes que presenta la empresa, así como fijar y clasificar las principales causas de estos problemas, todo esto con la finalidad de dar a conocer, estrategias confiables para solventarlos; para ello se debe cumplir con una serie de procesos metodológicos, mediante la aplicación del conocimiento científico, esto con la finalidad de lograr resultado óptimos, por lo tanto parar resolver una problemática, resulta conveniente tener un conocimiento detallado del tipo de investigación a realizar, el presente trabajo contempla el desarrollo, de un estudio de la unidad generadora de vapor, enmarcándose bajo la modalidad de un proyecto, **factible**.

Un proyecto factible, consiste en la investigación, elaboración y desarrollo de una propuesta, de un modelo operativo viable, para solucionar problemas, requerimientos o necesidades de organizaciones o grupos sociales. Puede referirse a la formulación de políticas, programas, tecnologías, métodos o procesos; el proyecto debe tener apoyo en una investigación de tipo, documental y de campo o un diseño que incluya ambas modalidades.

El estudio se delimitó, dentro de una investigación de carácter descriptiva, debido a que se puede medir toda la información recolectada, para luego describir, analizar e interpretar sistemáticamente, las características del fenómeno estudiado, con base en la realidad del escenario planteado.

En el presente trabajo se dieron a conocer las principales limitaciones de generación de vapor en la unidad número 1 de la Central termoeléctrica de Planta Centro CADAFE, así como los efectos, evaluados a corto y largo plazo que plantean estos problemas.

Todo esto permitió realizar un diagnostico, asertivo que hizo posible detectar en forma clara y objetiva, los distintos problemas, con el propósito de describirlos entender

su naturaleza y explicar sus causas y efectos de ahí que en función de los objetivos el estudio tenga su carácter descriptivo.

3.2 Fuentes de información

Las fuentes de información que se utilizaran, en este proyecto, son tanto primarias como secundarias, porque la recolección de los datos se hizo, basándose en información documental, provenientes de diferentes vías, como tesis, libros, manuales, planos de plantas, entrevista, revista e información electrónica.

Como fuente de información primaria se requiere de la información, que se adquiere directamente del contexto en el que se desarrolla el proyecto, por medio de entrevistas, con el personal de la empresa, vinculados en el entorno del problema, visitas a las áreas existentes, para extraer datos técnicos, y observaciones y mediciones de variables del sistema.

Como información secundaria, toda aquella que se encuentra, en escritos de personas que no se encuentran, directamente relacionadas con el problema, consultas de tipo bibliográfica, documental, como lo son libros de texto, normas, catálogos de fabricantes e internet, revisión de planos y material topográfico e informe de situación similares a la de la empresa.

3.3 Técnicas e instrumentos de recolección de datos.

Dado el nivel y los tipos de investigación antes mencionados, el primer pasó a realizar para lograr este proyecto, consistió en una observación directa, en periodos diarios para cada uno de los departamentos que conforman, la división de mantenimiento, observando todas sus actividades, todo esto para lograr evaluar el estado actual que presenta la empresa en especial la unidad, generadora de vapor en estudio.

De esta manera poder identificar las principales fallas, para luego establecer las estrategias y mejoras.

Una vez que seleccionamos el diseño de investigación apropiado, y la muestra adecuada de acuerdo con, nuestro problema de estudio e hipótesis, la siguiente etapa

consiste en recolectar los datos pertinentes, sobre las variables involucradas, en la investigación.

Para lograr recolectar toda esta información, y establecer un diagnostico efectivo, se dispuso de un instrumento de medición, para que una vez aprobado por la casa de estudio y la empresa, fuese aplicado bajo un método, que consiste en una técnica de observación sistemática participativa.

El instrumento consiste en la elaboración de un cuadro, en donde se establezcan todas las variables de estudio, además consta de un sistema de preguntas cerradas, seleccionados por su facilidad para ser respondidas y por ser más fácil de preparar, para su posterior análisis.

Posee de igual manera preguntas abiertas, lograr profundizar acerca de los problemas existentes en planta, esta herramienta no fue la única que ayudo a la recolección de información, para ello se necesitaron una serie de entrevistas no estructuradas, con los jefes y supervisores de área, personal operativo de planta y el tutor industrial, donde se pretendía conocer a fondo, el proceso de generación, maquinaria y equipos necesarios para lograr cumplir todas sus metas, así como conocer las posibles fallas en el sistema de generación de vapor.

3.4 Población y muestra.

La población y muestra de este proyecto estuvo basada, en los datos que suministra el departamento de calderas y auxiliares, donde se lleva un seguimiento de las variables asociadas a la caldera; de estos datos se obtuvo un promedio diario durante un mes de las variables involucradas para realizar la evaluación de rendimiento.

3.5 Fases de la investigación.

Estas etapas son las que se cumplieron durante el desarrollo de la investigación, a nivel macro para poder obtener la información y poder cubrir todos los objetivos previstos.

A continuación se presenta de forma resumida, las fases que siguió el proyecto:

Fase 1: Búsqueda de información

En esta fase del proyecto se identificó el objetivo de estudio partiendo del contexto, con el fin de estructurar un marco teórico que permitiera fundamentar dicho proyecto.

Para realizar esta base fue necesario, recolectar cierta cantidad de información de distintas fuentes bibliográficas, experiencias del personal de la empresa vinculados en el entorno del problema, tesis de grados, manuales de operación y mantenimiento, sitios web, revistas, con la finalidad de indagar, consultar recopilar, agrupar y organizar adecuadamente, la información que se utilizó dentro de la misma.

En esta fase también se, seleccionó una metodología de investigación que se consideró valida, para aplicarla a diferentes investigaciones que poseen características similares a las que se requiere realizar.

Fase 2: Elaboración del instrumento.

Una vez revisada, analizada e interpretada la información que se seleccionó para la investigación, se comenzó a elaborar un instrumento o plan de trabajo que facilitó la recopilación de información, en las diferentes divisiones, departamentos y áreas complementarias de la empresa y a su vez elaborar un diagnostico energético y detectar, las posibles pérdidas de energía en los sistemas de generación y distribución de vapor, para ello se llevaron una serie de pasos con la finalidad de cumplir con los objetivos planteados, al inicio del proyecto. **Ver anexo A**

El diagnostico energético del sistema, permitió determinar en primer lugar.

1. La eficiencia de la caldera conforme a los métodos indicados por el código ASME PTC 4.1 (Ver apéndice) de calderas y recipientes a presión.
2. Determinar el comportamiento del aislamiento térmico, conforme a los métodos indicados en la norma ASME B31.3 aislamientos térmicos industriales.
3. Estimar las pérdidas, fugas de vapor, trampas para vapor de agua en línea de distribución de vapor.

Fase 3: Aplicación del instrumento.

En esta fase de la investigación se realizaron, una serie de visitas a toda la planta con la finalidad de observar, cada una de las partes que conforman la unidad generadora de vapor, equipos auxiliares, tuberías, válvulas y herramientas de forma operativa, para así poder tener una visión del estado actual de los sistemas, que conforman dicha unidad y observar directamente a al operario, durante su jornada diaria, además se procedió a realizar una serie de entrevistas, no estructuradas a cada uno de los jefes, de los departamentos, supervisores, trabajadores y al personal de la compañía contratada en las labores de modernización de la empresa, para así identificar cualquier inconveniente, que no puede ser perceptible a simple vista o problemas que se encuentran en lugares de acceso riesgoso o difícil acceso.

Fase 4: Diagnóstico de la situación actual.

Toda la información recogida, en la fase anterior es analizada en esta fase, con la finalidad de evaluar el estado actual de todos los equipos, que conforman la unidad generadora de vapor, para ello se aplico el instrumento de medición, a toda la población y muestra seleccionada y se relacionó dicha información con los objetivos planteados, en las primeras etapas del proyecto, y se pudieron obtener respuestas a las incógnitas planteadas al principio del estudio.

Fase 5: Aplicación de herramientas.

Una vez culminadas todas las fases anteriores de la investigación, se darán una serie de análisis adicionales, por medio del desarrollo de las herramientas seleccionadas, entre la empresa, el investigador y la casa de estudio, estas herramientas permitieron clasificar y estructurar los problemas, encontrados en la central Termoeléctrica de Planta Centro CADAFE, para de esta manera obtener soluciones o estrategias que en realidad sean efectivas y ataquen los problemas.

Fase 6: Creación de estrategias.

En esta fase de la investigación, se propusieron una serie de estrategias a los problemas más críticos presentes, en la unidad generadora de vapor y así poder

recuperar la capacidad instalada de la unidad número 1 de la Central termoeléctrica de Planta Centro CADAFE.

3.6 Metodología de cálculo.

3.6.1 Método directo

De la Ecuación 2.1 del capítulo 2 se obtiene el rendimiento de la caldera de forma directa.

$$Eficiencia = \frac{Energía\ saliente}{Energía\ Entrante} x100 \qquad \text{E.C 2.1}$$

3.6.1.1 Cálculo de la energía saliente:

La energía saliente es el calor aprovechado en el sistema, para obtenerlo es necesario conocer el flujo másico de agua a la entrada y el flujo másico de vapor a la salida con sus respectivas entalpias, para ello se emplea la ecuación 3.1

$$Q^0{}_{APROVECHADO} + \left(\dot{M}_1 * h_1\right) + \left(\dot{M}_3 * h_3\right) = \left(\dot{M}_2 * h_2\right) + \left(\dot{M}_4 * h_4\right) + \dot{W} \qquad \text{E.C 3.1}$$

3.6.1.2 Cálculo de la energía entrante:

La energía entrante es el calor introducido al sistema para obtenerlo es necesario conocer el flujo másico de combustible con su respectivo poder calorífico y se obtiene a través de la ecuación 3.2

$$Q_{INTRODUCIDO} = \dot{M}_{COMBUSTIBLE} * Pc \qquad \text{E.C 3.2}$$

Una vez conocidos los valores de la energía saliente y entrante se sustituyen en la ecuación 2.1 para obtener el rendimiento de la caldera.

3.6.2 Método indirecto

De la Ecuación 2.2 del capítulo 2 se obtiene el rendimiento de la caldera de forma indirecta.

$$\eta_{CALDERA} = \left(1 - \frac{\sum P}{PCI}\right) * 100 \qquad \text{E.C 2.2}$$

Este método requiere del cálculo de una serie de pérdidas que a continuación se presentan los datos y cálculos que se requieren para obtener dichas pérdidas:

- **Pérdidas por Gas Seco.**

$$Pas = G_{SE} x C_{EG} x (T_{nc} - T_{as}) \qquad \text{E.C 3.3}$$

Donde:

Pas= Pérdidas por gas seco.

G_{SE}= Gas seco a la salida del economizador

C_{EG}= Calor específico del gas de combustible

Tnc= Temperatura de salida del recalentador

Tas= Temperatura del aire seco

- **Pérdida por Humedad en el Combustible.**

$$Phc = H_2O(ha - hg) \qquad \text{E.C 3.4}$$

Donde:

Phc= Pérdidas por humedad en el combustible

ha= Entalpía del aire

hg= Entalpía del gas

H_2O= Cantidad de agua presente en el combustible

- **Pérdidas por Hidrogeno presente en la Combustión.**

$$Ph_{2c} = 8{,}936xHx(ha - hg) \qquad \text{E.C 3.5}$$

Donde:

Ph_{2c}= Pérdidas por hidrogeno presente en la combustión

H= Cantidad de hidrogeno presente en el combustible

ha= Entalpía del aire

hg= Entalpía del gas

- **Pérdida por Humedad en el Aire.**

$$Pha = HaxAs(ha - hg) \qquad \text{E.C 3.6}$$

Donde:

Pha= Pérdidas por humedad en el aire

Ha= Humedad absoluta

As= Cantidad de aire seco

ha= Entalpía del aire

hg= Entalpía del gas

- **Perdidas por monóxido de carbono (CO).**

$$PCO = \frac{CO}{CO_2 - CO} x5640xC \qquad \text{E.C 3.7}$$

Donde:

PCO= Pérdidas por monóxido (CO).

CO= Cantidad de monóxido (CO) presente en los gases productos de la combustión.

CO_2= Cantidad de dióxido de carbono (CO_2) presente en los gases productos de la combustión.

C= Cantidad de carbono (C) presente en el combustible.

Una vez calculadas todas las pérdidas se realiza una sumatoria y conocido ya el poder calorífico inferior se sustituyen la EC 2.2 y se obtiene el rendimiento de la caldera de forma indirecta.

CAPITULO IV

4.1 Desarrollo del proyecto

Es evidente que con el primer objetivo del proyecto que consiste en analizar la generación de vapor en la caldera de la unidad número 1 y evaluar el funcionamiento de sus componentes, se efectuó un diagnostico energético para determinar las posibilidades potenciales, de ahorro de energía en los sistemas de generación y distribución de vapor.

1. Este diagnostico energético del sistema pretende determinar la eficiencia de la caldera conforme a los métodos indicado por el código ASME PTC 4.1 (Ver anexo D).
2. Determinar el estado actual del aislamiento térmico.
3. Estimar las pérdidas de energía en fuga de vapor en las líneas de distribución de vapor.

Las actividades que se realizaron para cubrir el objetivo, se exponen con la amplitud y profundidad necesaria para obtener una visión global del uso energético de los equipos o sistemas, así como las posibilidades de optimizarlo, de este modo se realizaron una serie de pasos, que se mencionan a continuación:

Análisis energético del sistema original.

La búsqueda de información no es más que la indagación acerca del tema u objetivos que se plantea el proyecto, en diferentes fuentes primarias y secundarias, como se comento en el capítulo 3.

Los datos del diseño original, fueron seleccionados de los manuales de operación y mantenimiento, de las calderas BORSIG, del sistema de generación y distribución de vapor, así como de documentos que muestran el historial de la unidad número 1.

Para lograr determinar la eficiencia de la caldera, en su estado original siguiendo los métodos expuestos en el capítulo 2, se cuantificaron distintas variables especificadas en la tabla 4.1 que a continuación se describe.

Tabla 4.1: Parámetros de operación del sistema original Versus el sistema actual para una carga de 300 MW.

Presión	Unidad	Sistema Original. Carga 300 MW	Sistema Operación Actual. Carga 200 MW
Admisión del agua de alimentación economizador	Kg/cm^2	183	132,6
Descarga del Sobrecalentador terciario	Kg/cm^2	183	132,6
Admisión del recalentador	Kg/cm^2	31,5	41
Descarga del recalentador	Kg/cm^2	29,8	42,56
Temperatura			
Admisión del agua de alimentación economizador	^0C	234	230
Descarga del Sobrecalentador terciario	^0C	540	538
Admisión del recalentador	^0C	318	375
Descarga del recalentador	^0C	540	538
Entalpía			
Agua de admisión del agua de alimentación economizador	KJ/Kg	1012,16	976,92
Descarga del Sobrecalentador terciario	KJ/Kg	3390,33	3439,75
Admisión del recalentador	KJ/Kg	3037,9	3154,66
Descarga del recalentador	KJ/Kg	3549,5	3531,09
Tasa de Flujo			
Agua de alimentación	Kg/h	258,41	272,15
Vapor del recalentador	Kg/h	240,48	229,9
Tasa de combustible	Kg/h	18,75	19,66

- Para evaluar la eficiencia de la caldera se utilizaron dos métodos: uno directo y otro indirecto.

En el método directo: se aplica el principio de conservación de energía expuesto en el capítulo 2, para determinar la eficiencia de la caldera, estableciendo puntos de control y especificando las variables a utilizar, para ver los detalles de cálculo **ver apéndice 1**.

Para calcular el rendimiento o eficiencia de la caldera se implementaron los métodos expuestos en siguiendo las normas ASME PTC 4.1 (**Ver anexo D**).

Para ello el método directo se utilizó el mismo procedimiento que aplica para determinar, el rendimiento o eficiencia de cualquier clase de equipo energético, siendo el rendimiento o eficiencia la diferencia entre la energía útil de salida, por la de entrada.

Los resultados obtenidos a través del método directo se muestran en la **tabla 4.2**

Tabla 4.2 Comparación de eficiencias obtenidas por el método directo:

Variables	Condición Nominal	Condición Actual
Carga	300 MW	300 MW
Eficiencia	98,5 %	90,6 %

Hay una caída de eficiencia de 7,8 % con respecto al rendimiento del sistema en condiciones nominales.

En cuanto al método, indirecto las pérdidas tomadas en el cálculo de la eficiencia de la caldera de la unidad número 1 de la central termoeléctrica planta centro fueron las siguientes:

- Pérdidas por gas seco.
- Pérdidas por la humedad del combustible.
- Pérdida por hidrógeno presente en la combustión.
- Pérdida por la humedad del aire.

Para ver los detalles de cálculo **ver apéndice 2**.

Los resultados obtenidos por el método directo se muestran en la **tabla 4.3**

Tabla 4.3 Comparación de eficiencias obtenidas por el método directo e Indirecto

Variables	Condición Nominal	Condición Actual
Carga	300 MW	300 MW
Eficiencia Método Directo	98,5 %	90,6 %
Eficiencia Método Indirecto	98,5 %	89,1 %

Hay una caída de la eficiencia de 7,8 % con el método directo y con el método indirecto 9,4 % respecto al sistema en condiciones nominales.

4.2 Diagnostico de la situación actual

Motivado a las extensas áreas que ya han sido evaluadas, se hizo necesario realizar esta etapa del diagnostico de la situación actual de manera separada, para cada uno de los sistemas, que completan la unidad generadora de vapor de la central termoeléctrica Planta Centro CADAFE, con la finalidad de recaudar la mayor información posible, acerca de cada uno de los problemas encontrados, en los sistemas y subsistemas de la caldera, que fueron fuente de estudio y de observación, durante el período programado.

En general la unidad generadora de vapor, presenta un estado de deterioro, avanzado por la falta de mantenimiento preventivo y predictivo por parte de la empresa, agregado a esto la influencia del medio externo de trabajo, ya que la planta está ubicada a orillas del mar atacando severamente los equipos y acortando su vida útil. Como se observó en el diagnostico energético, el sistema actual presenta una disminución de la eficiencia con respecto al sistema original, esto es motivado por las diversas fugas de energía en el sistema, las causas por las cuales hay esta diferencia entre los valores de eficiencia son:

1. Envejecimiento y ensuciamiento de las superficies intercambiadoras de calor.
2. Combustión no optima.
3. Exceso de oxigeno.
4. Fugas.
5. Funcionamiento no eficiente de los equipos. **(Ver anexo B Figura B.10)**

Es por tal razón que se realiza una descripción, de la situación actual de los distintos sistemas que conforman a la caldera, ubicando el problema y planteando estrategias.

Los equipos que integran el sistema de combustible de la caldera, se encuentran en estado de deterioro, **(Ver anexo B figura B.5)** esto se deben a la falta de mantenimiento preventivo y predictivo, por parte de la empresa, ocasionando la disminución de confiabilidad del equipo y aumentando las fallas en los equipos del

sistema descrito. Además hay que tomar en cuenta la influencia del medio externo de trabajo, ya que la planta está ubicada, a orilla del mar, atacando severamente por la corrosión acortando su vida útil.

Durante las inspecciones realizadas, al sistema de combustible, el personal encargado de su mantenimiento y operación, indico que el funcionamiento actual y los inconvenientes que suelen presentarse en dicho sistema, se deben a lo siguiente:

1. Perdidas de aislantes en las líneas de vapor de trazas, **(Ver anexo B Figura B.6 y B.7)** realizada la inspección a la líneas de vapor de trazas, se notó que la gran cantidad de materiales aislantes fue retirado de las tuberías y válvulas para reparar fugas, y no fue repuesto, esto origina perdidas por radiación, ocasionando que el combustible pierda parte de su viscosidad y no llegue al quemador en las condiciones y temperaturas requeridas. La solución es reponer el aislante y carcasas para evitar las perdidas.
2. Quemadores: Unos de los problemas más críticos que presenta la caldera es en el área de quemadores, en el registro de paradas de la unidad número 1, de años anteriores se observó que la caldera incremento su número de disparos, y la gran mayoría se atribuye a los quemadores. Con la inspección realizada al área, se notó que los quemadores no operan de una manera efectiva, el principal problema se presenta en la boquilla del quemador, ya que el combustible no se atomiza bien y produce una mezcla impura, produciendo una mala combustión en el hogar. Para la solución de este problema y por experiencia tomadas en la unidad número 2 del complejo termoeléctrico, se presenta la propuesta planteada por ALSTOM POWER, sustituir el atomizador de flujo doble con tobera, por el quemador de núcleo de llama estratificada de modo radial, que está diseñado para quemar combustible pesado número 6 y gas natural en calderas industriales, mientras mantiene el rendimiento de la unidad y cumple con los requisitos medio ambientales a nivel de las emisiones de oxido de nitrógeno y monóxido de carbono. El quemador aplica tres principios asociados, a la combustión de combustibles fósiles, por el NOx.

- Encendido temprano del combustible con condiciones del combustible enriquecido.
- Graduar el proceso de combustión. **(Ver anexo B figura B.12)**
- Aumento del tiempo de residencia de combustible.

4.3 Situación actual del sistema aire-gas

Los equipos que integran al sistema de aire-gas de la caldera número 1 presentan, mayor deterioro debido a la falta de mantenimiento preventivo y predictivo por parte de la empresa, en las inspecciones realizada a los equipos que integran al sistema se observó lo siguientes:

Ventiladores:

- Ventiladores recirculadores de gases: los ventiladores recirculadores de gases de la unidad 1, están operando muy por debajo de su funcionamiento optimo; esto equipos tienen la función importante de controlar y elevar la temperatura de los elementos que se encuentran en la zona convectiva, de la caldera tomando parte de los gases de escape antes de su entrada al recalentador y lo introduce por la parte inferior del hogar, a una temperatura aproximada de 334 ^{0}C, con esto se consigue aumentar el flujo ascendente, de gases caliente lo cual se manifiesta con un aumento de la temperatura del vapor recalentado, y el agua de alimentación a la salida del economizador, por esta razón es importante la reincorporación de estos dispositivos a su valor nominal de funcionamiento, si se requiere recuperar la máxima carga residual. **(Ver anexo B figura B.8 y B.9)**

  Se proponen colocar unos ventiladores con las mismas especificaciones técnicas.

4.4 Conclusiones

1. De acuerdo al estudio realizado a la unidad generadora de vapor y sus subsistema, se logró demostrar que los equipos presentan un estado no eficiente, ya que su eficiencia actual es de 89,1% el cual disminuye con el pasar del tiempo, sino se toman las medidas necesarias para su recuperación, además el mantenimiento preventivo, que juega un papel importante para aumentar la confiabilidad y disponibilidad de los equipos.
2. La temperatura, la presión dentro del hogar de la caldera y el aire requerido para una combustión óptima, constituyen factores importantes en la generación de vapor, estos factores deben estar monitoreados constantemente para lograr el máximo rendimiento de la caldera; la temperatura actual de admisión al recalentador es de 375 °C la cual indica un incremento 15% respecto a la nominal; el exceso de aire actual es de 1,6 comparado con el nominal que oscila entre (1 – 1.1) indica que hay un incremento que afecta de manera negativa la combustión en la caldera.
3. El cálculo del rendimiento de la caldera para un sistema original se obtuvo a través de dos métodos diferentes y se comparó con el de operación actual, determinando una caída de la eficiencia, 9,4 % respecto al sistema en condiciones nominales, dejando claro que la unidad presenta varias fallas, que la limitan; además se puede observar que actualmente la caldera está quemando 19,66 Ton/h de combustible 5% más de lo normal, esto con la finalidad de cubrir las pérdidas en el sistema.
4. Realizando las propuestas sugeridas en el diagnostico actual y en las recomendaciones se puede obtener el aumento de la eficiencia, permitiendo de esta manera incrementar y aprovechar mejor el flujo másico de vapor que actualmente es de 272,15 Ton/h el cual puede incrementarse entre (7 - 10) % más logrando un aumento de la potencia de generación en la turbina.

4.5 Recomendaciones.

Para lograr que el complejo termoeléctrico de Planta Centro CADAFE, pueda recuperar la capacidad instalada en la unidad número 1, aumentando su rendimiento se recomienda:

1. Realizar manuales de mantenimiento preventivos para cada uno, de los equipos que conforman la caldera y sus sistemas auxiliares, con la finalidad de realizar un programa de mantenimiento acorde, con los requerimientos de dichos equipos.
2. Dotar a los trabajadores, con herramientas de trabajo adecuadas y orientaciones sobre las nuevas tecnologías de mantenimiento total que existen hoy día.
3. Se recomienda realizar una debida, limpieza de las piezas internas, de la caldera para remover la gran cantidad de sedimentos minerales internos, adheridos a los elementos de transferencia de calor.
4. Realizar una limpieza química a los tubos internos, con la finalidad de remover los excesos, de magnetitas presentes, los cuales a demás de afectar la transferencia de calor pueden ocasionar rupturas de las demás tuberías.

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Apéndice 1

Método Directo

- **Descripción de cada uno de los estados que muestra el esquema de la figura 4.1 en condiciones nominales, para una carga de 300 MW.**

Esquema de los puntos de control

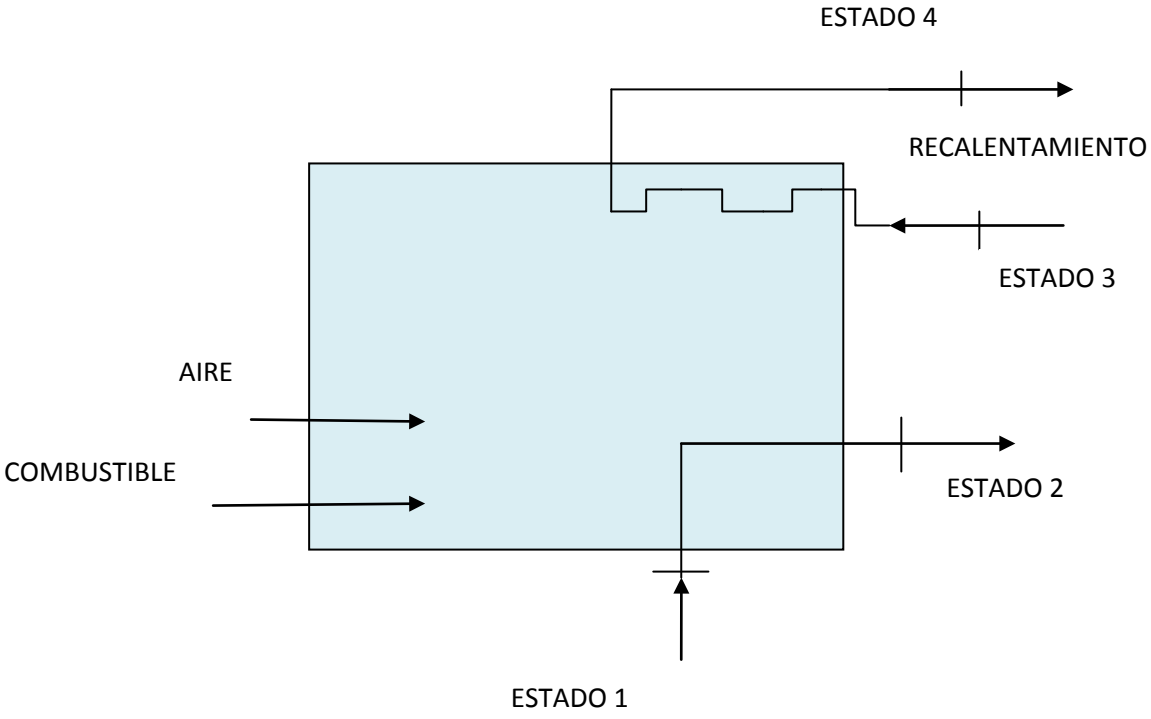


Figura AP.1. Esquema de los puntos de control.

$$\eta_{CAL} = \frac{Q^0{}_{APROVECHADO}}{Q^0{}_{INTRODUCIDO}} \qquad \text{E.C 2.1}$$

Donde:

$Q_{APROVECHADO}$= Energía saliente (KW)

$Q_{INTRODUCIDO}$= Energía entrante (KW)

$$Q^0{}_{APROVECHADO} + (\dot{M}_1 * h_1) + (\dot{M}_3 * h_3) = (\dot{M}_2 * h_2) + (\dot{M}_4 * h_4) + \dot{W} \quad \text{E.C 3.1}$$

Donde:

W= 0

$$Q_{INTRODUCIDO} = \dot{M}_{COMBUSTIBLE} * Pc \quad \text{E.C 3.2}$$

Estado 1: Admisión del agua de alimentación

$P_1 = 183\ Kg/cm^2$ $h_1 = 1012{,}16\ KJ/Kg$

$P_1 = 179{,}3\ Bar$ $T_1 = 234\ °C$

$M_1 = M_2 = 930300\ Kg/s$

$M_1 = M_2 = 258{,}41\ Kg/h$

Estado 2: Descarga del Sobrecalentador terciario

$P_2 = 183\ Kg/cm^2$ $h_2 = 3390{,}33\ Kj/Kg$

$P_2 = 179{,}3\ Bar$ $T_2 = 540\ °C$

$M_1 = M_2 = 930300\ Kg/s$

$M_1 = M_2 = 258{,}41\ Kg/h$

Estado 3: Admisión del recalentador

$P_3 = 31{,}5\ Kg/cm^2$ $h_3 = 3037{,}9\ Kj/Kg$

$P_3 = 30{,}5\ Bar$ $T_3 = 318\ °C$

$M_3 = M_4 = 865750\ Kg/s$

$M_3 = M_4 = 240{,}48\ Kg/h$

Estado 4: Descarga del recalentador

$P_4 = 29{,}8\ Kg/cm^2$ $h_4 = 3549{,}5\ Kj/Kg$

$P_4 = 27{,}41\ Bar$ $T_4 = 540\ °C$

$M_3 = M_4 = 715394{,}4\ Kg/s$

$M_3 = M_4 = 198{,}7\ Kg/h$

$\dot{Q}Aprovechado = M_{1,2}(h_2 - h_1) + M_{3,4}(h_4 - h_3)$

$\dot{Q}Aprovechado = 258{,}41(3390{,}33 - 1012{,}16) + 240{,}48(3549{,}5 - 3037{,}9)$

$\dot{Q}Aprovechado = 737572{,}47\ KW$

Poder Calorífico del Gas Natural:

PCI= Poder calorífico inferior

PCI= 39900 Kj/Kg

$M_{Combustible} = 67530\ Kg/s$

$M_{Combustible} = 18{,}75\ Kg/h$

$Q_{INTRODUCIDO} = \dot{M}_{COMBUSTIBLE} * Pc$

Con el PCI= 39900 Kj/Kg

$Q_{INTRODUCIDO} = 18{,}75 * (39900) = 748125\ KW$

$$\eta_{CAL} = \frac{737572{,}47}{748125} * 100 = 98{,}5\ \%$$

Resultado para una carga de 300 MW en condiciones nominales 98,5 % de eficiencia.

- **Cálculo de Rendimiento en condiciones actuales de operación, para una carga de 300 MW.**

Estado 1: Admisión del agua de alimentación

$P_1 = 132{,}6\ Kg/cm^2$ $h_1 = 976{,}92\ KJ/Kg$

$P_1 = 130\ Bar$ $T_1 = 230\ °C$

$M_1 = M_2 = 979759{,}5\ Kg/s$

$M_1 = M_2 = 272{,}15\ Kg/h$

Estado 2: Descarga del Sobrecalentador terciario

$P_2 = 132{,}6\ Kg/cm^2$ $h_2 = 3439{,}75\ Kj/Kg$

$P_2 = 130\ Bar$ $T_2 = 538\ °C$

$M_1 = M_2 = 979759{,}5\ Kg/s$

$M_1 = M_2 = 272{,}15\ Kg/h$

Estado 3: Admisión del recalentador

$P_3 = 41\ Kg/cm^2$ $h_3 = 3154{,}66\ Kj/Kg$

$P_3 = 40\ Bar$ $T_3 = 375\ °C$

$M_3 = M_4 = 827982\ Kg/s$

$M_3 = M_4 = 229{,}9\ Kg/h$

Estado 4: Descarga del recalentador

$P_4 = 42{,}56\ Kg/cm^2$ $h_4 = 3531{,}09\ Kj/Kg$

$P_4 = 41{,}7\ Bar$ $T_4 = 538\ °C$

$M_3 = M_4 = 827982\ Kg/s$

$M_3 = M_4 = 229{,}9\ Kg/h$

$\dot{Q}Aprovechado = M_{1,2}(h_2 - h_1) + M_{3,4}(h_4 - h_3)$

$\dot{Q}Aprovechado = 272{,}15(3439{,}75 - 976{,}92) + 229{,}9(3531{,}09 - 3154{,}66)KW$

$\dot{Q}Aprovechado = 756800{,}44\ KW$

Poder Calorífico del Gas Natural:

PCI= 41880,5 Kj/Kg

Nota: Este fue obtenido de los registros que llevan los operadores de planta

$M_{Combustible} = 70780\ Kg/s$

$M_{Combustible} = 19{,}66\ Kg/h$

$Q_{INTRODUCIDO} = \dot{M}_{COMBUSTIBLE} * Pc$

Con el PCI= 41880,5 Kj/Kg

$Q_{INTRODUCIDO} = 19{,}66 * (41880{,}5) = KW$

$$\eta_{CAL} = \frac{756800{,}44}{835050} * 100 = 90{,}6\ \%$$

Resultado para una carga de 300 MW en condiciones actuales 90,6 % de eficiencia.

Tabla AP1.1 Comparación de eficiencias obtenidas por el método directo:

Variables	Condición Nominal	Condición Actual
Carga	300 MW	300 MW
Eficiencia	98,5 %	90,6 %

Hay una caída de eficiencia de 7,8 %

Apéndice 2

Método Indirecto

Nota: Para el cálculo de la eficiencia no se tomó en consideración, las pérdidas de vapor por purgas continúa en el domo por recomendación de los ingenieros y técnicos de la empresa ALSTOM POWER, además es una perdida vapor muy insignificante para el gran flujo de agua manejado, por la caldera y se desprecia.

Para obtener los resultados de métodos directos, deberán determinarse las siguientes pérdidas:

1. Pérdida debida a la humedad del combustible: esto es especialmente aplicable, al carbón que se lava, o que se almacena en el exterior, para otros combustibles se considera una perdida, inherente con poca, perspectiva de reducción, a no ser por un cambio o sustitución del combustible.
2. Pérdida debida a la combustión del hidrógeno del combustible: es una pérdida que forma agua (humedad), y va a la chimenea con vapor, el combustible y el aceite tiene la mayor cantidad de hidrógeno, está perdida es considerada también inherente no controlable a no ser que se cambien las especificaciones del combustible.
3. Pérdidas debida a la humedad del aire usado para la combustión: esta es una perdida que trae como consecuencia, un precalentamiento del aire en las calderas grandes de vapor, de otra manera se considera también una perdida inherente originada por el uso del aire ambiente en la combustión del combustible.
4. Pérdida debida al calor llevado a la chimenea por los gases de combustión: los factores que pueden inferir en esta pérdida incluirán:
   - El alto exceso de aire revelado por un análisis de los gases de combustión.
   - Suciedad e incrustación de la superficie de transferencia de calor del lado del agua y del fuego o gases.
   - Pobre circulación de agua en comparación con los flujos del lado de gases de combustión.
   - Las velocidades de los gases demasiado altas, a través de la caldera (demasiado tiro), de forma que no hay tiempo suficiente para la transferencia de calor adecuada.
5. Pérdida debida a la combustión incompleta:
   - Suministro de aire insuficiente.

- Hogar frio a baja carga.
- Pobre atomización o pulverización del combustible.

6. Pérdidas diversas por radiación convección y fugas: estas pérdidas se pueden producir por:
   - Débil aislamiento alrededor del calderin y paredes.
   - Necesidad de reparación de los refractarios del hogar.
   - Tuberías, juntas, sellados de uniones y otras fugas por las paredes de la caldera.

- **Descripción de cada uno de las variables ambientales.**

Análisis del combustible expresado en porcentaje de peso (Manual de operaciones)

Datos del aire (Entrada de los ventiladores de tiro forzado)

Temperatura de aire seco (Tas)= 29 ^{0}C

Temperatura aire húmedo (Tah)= 25 ^{0}C

Humedad relativa (Hr)= 65,2 %

Presión de saturación del aire seco (Psat)= 30,5 mmHg= 4,06 MPa

Presión atmosférica (Pa)= 760 mmHg

Calor especifico del aire (C_{EA})= 0,24 Kcal/Kg-^{0}C

Humedad Absoluta (Ha)

$$Ha = \frac{0{,}6622 * PP}{Pa - PP}$$

Donde:

Pa= Presión atmosférica

PP= Presión Parcial del vapor

$$PP = \frac{Hr}{100} * P_{SAT}$$

$$PP = \frac{65,2}{100} * 30,5 = 19,89\ mmHg$$

$$Ha = \frac{0,6622 * 19,89}{760 - 19,89} = 0,01672\ Kg/Kg$$

Análisis de los gases (Orsat)

Salida del economizador % Volumen

Oxigeno (O_2)= 0,43 %

Dióxido de carbono (CO_2)= 16,1 %

Nitrógeno (N_2)= 83 %

Monóxido de carbono (CO)= 0%

Salida del intercambiador

Oxigeno (O_2)= 1,05 %

Dióxido de carbono (CO_2)= 15,6 %

Nitrógeno (N_2)= 83,35 %

Monóxido de carbono (CO)= 0%

Para los cálculos de eficiencia se puede tomar el calor específico internacional de los humos secos a 150 ^{0}C, el cual es 0,24 Kcal/Kg.^{0}C Equivalente a 1005 KJ/Kg.^{0}C

Cantidad de gas seco a la salida del economizador (Gse)

$$G_{SE} = \frac{(44{,}01 * CO_2) + (32 * O_2) + (28{,}02 * N_2) + (28{,}02 * CO)}{12{,}01(CO_2 + CO)}\left(C + \left(\frac{12{,}01}{32{,}07} * S\right)\right)$$

$$G_{SE} = \frac{(44{,}01 * 0{,}161) + (32 * 0{,}009) + (28{,}02 * 0{,}83) + (28{,}02 * 0)}{12{,}01(CO_2 + CO)}\left(0{,}8709 + \left(\frac{12{,}01}{32{,}07} * 0{,}0142\right)\right)$$

$G_{SE} = 13{,}88\ Kg/Kg$

Cantidad de nitrógeno N2 a la salida del economizador

$$N_{GSE} = \frac{28{,}02 * N}{12{,}01 * (CO_2 + CO)} * \left(C + \left(\frac{12{,}01}{32{,}07} * S\right)\right)$$

$$N_{GSE} = \frac{28{,}02 * 0{,}83}{12{,}01 * (0{,}161 + 0)} * (0{,}87622) = 10{,}53\ Kg/Kg$$

Cantidad de aire seco (As)

$$As = \frac{N_{GSE} - N_2}{0{,}7685}$$

$$As = \frac{10{,}53 - 0{,}0059}{0{,}7685} = 13{,}70\ Kg/Kg$$

Tabla AP.2.1 Vapor de atomización (Va)

400 MW	0,08 Kg/Kg
300 MW	0,08 Kg/Kg
200 MW	0,08 Kg/Kg

Humedad en el Gas a la salida del economizador (Hgse)

$$H_{gSE} = (8{,}936 * H) + (Ha * As) + Va$$

$$H_{gSE} = (8{,}936 * 0{,}1032) + (0{,}01672 * 13{,}70) + 0{,}08 = 1{,}23\ Kg/Kg$$

Cantidad de aire seco a la salida del intercambiador (Gsl)

$$G_{SL} = \frac{(44{,}01 * CO_2) + (32 * O_2) + (28{,}02 * N_2) + (28{,}02 * CO)}{12{,}01(CO_2 + CO)}\left(C + \left(\frac{12{,}01}{32{,}07} * S\right)\right)$$

$$G_{SL} = \frac{(44{,}01 * 0{,}156) + (32 * 0{,}01) + (28{,}02 * 0{,}8335) + (28{,}02 * 0)}{12{,}01(CO_2 + CO)}\left(0{,}870 + \left(\frac{12{,}01}{32{,}07} * 0{,}0142\right)\right)$$

$G_{SL} = 14{,}28\ Kg/Kg$

Cantidad de humedad a la salida del intercambiador (ChSL)

$$C_{hSL} = H_{HSE} + (G_{SL} - G_{SE}) * Ha$$

$$C_{hSL} = 1{,}23 + (14{,}28 - 13{,}88) * 0{,}0167 = 1{,}237\ Kg/Kg$$

Cantidad de fuga en el intercambiador (FL)

$$FL = \frac{G_{SL} + C_{hSL} - (H_{GSE} - G_{SE})}{G_{SE} + H_{GSE}}$$

$$FL = \frac{14{,}28 + 1{,}237 - (1{,}23 - 13{,}88)}{13{,}88 + 1{,}23} * 100 = 2{,}71\ \%$$

Temperatura de aire entrada al intercambiador (Tael)

Tael= 80 ^{0}C

Temperatura del gas a la salida del intercambiador (Tgsl)

Tgsl=150 ^{0}C

Temperatura corregida

$$T_C = \frac{FL * C_{ea}(T_{gsL} - T_{aeL})}{100 * C_{eg}} + T_{gsL}$$

Donde:

Cea= Calor especifico del aire= 0,24

Ceg= Calor especifico del Gas= 0,24

Pérdidas en la Caldera.

1. Pérdidas de aire seco (Pas)

$$Pas = G_{SE} * C_{eg} * (Tc - Tas)$$

$$Pas = 13{,}88 * 0{,}24 * (150 - 29) = 1687{,}57\ \frac{KJ}{Kg}$$

2. Pérdidas por humedad en el combustible (Phc)

$$Phc = H_2O * (ha - hg)$$

$$Phc = 0{,}001 * (582{,}89 - 298{,}17) = 1{,}17 \frac{KJ}{Kg}$$

3. Perdidas por hidrógeno presente en el combustible (PH_{2C})

$$PH_{2C} = 8{,}936 * H * (ha - hg)$$

$$PH_{2C} = 8{,}936 * 0{,}1036 * (582{,}89 - 298{,}17) = 1103{,}55 \frac{KJ}{Kg}$$

4. Pérdidas por humedad en el aire (Pha)

$$Pha = Ha * As * (ha - hg)$$

$$Pha = 0{,}1016 * 13{,}70 * (582{,}89 - 298{,}17) = 1659{,}22 \frac{KJ}{Kg}$$

5. Pérdidas por CO(P_{CO})

$$P_{CO} = \frac{CO}{CO_2 - CO} * 5640 * C$$

Por partir de una combustión completa las pérdidas por CO en el combustible son cero, ya que hay presencia de monóxido de carbono en los gases de combustión.

6. Pérdidas por radiación (P_{RAD})

$$P_{RAD} = P_{RAD} * VCS * \frac{1}{100}$$

Siendo P_{RAD} el porcentaje de la carta ASME PTC 4,1

Tabla AP.2.2 Pérdidas por radiación

Carga	Pérdida por radiación
400 MW	150,72 KJ/Kg
300 MW	110,95 KJ/Kg
200 MW	81,64 KJ/Kg

Sumatoria de las pérdidas calculadas:

$$\sum P = P_{as} + P_{hc} + P_{h2C} + P_{ha} + P_{CO} + P_{RAD}$$

Finalmente la eficiencia de la caldera

$$\eta_{CALDERA} = \left(1 - \frac{\sum P}{PCI}\right) * 100$$

PCI= 41880,5 Kj/Kg

Nota: Este poder calorífico fue obtenidos de los registros que llevan los operadores de planta)

$$\eta_{CALDERA} = \left(1 - \frac{4562,46}{41880,5}\right) * 100$$

$$\eta_{CALDERA} = 89,1\ \%$$

Tabla AP.2.3 Comparación de eficiencias obtenidas por el método directo e Indirecto

Variables	Condición Nominal	Condición Actual
Carga	300 MW	300 MW
Eficiencia Método Directo	98,5 %	90,6 %
Eficiencia Método Indirecto	98,5 %	89,1 %

Hay una caída de la eficiencia de 7,8 % con el método directo y con el método indirecto 9,4 %

1.- **DATOS GENERALES DE LA CALDERA**

1.1 Tipo de caldera: Acuotubular ____ Pirotubular ____ CTE____

1.2 Marca:

1.3 Año de fabricación:

1.4 País de procedencia:

1.5 Tipo de combustible que utiliza: Fuel Oil ___ Diesel ___ Bagazo ___ Gas ___ Crudo Nacional ___

1.6 Tipo de hogar: Al vacío ____ Presurizado ____

CARACTERISTICAS DE LOS TIROS

1.6 Inducido mecánico ____ Ind. Natural ____ Forzado Mecánico

1.7 Horas de trabajo al año:

1.8 Posee: Sobrecalentador __ Economizador ___ Calentador Aire ____

1.9 Posee precalentador del agua de alimentar? SI ____ NO ____

TIPO DE ATOMIZACION

1.10 Mecánica____ Mecánica con Vapor ____ Copa Rotatoria ___

1.11 Posee precalentamiento del combustible? SI____ NO____

1.12 Entrega Vapor: Saturado _____ Sobrecalentado _____

1.13 Posee tratamiento del agua de alimentar? SI____ NO____

1.14 Posee sistema de limpieza de superficie? SI____ NO____

1.15 Se realizan análisis de gases periódicos? SI____ NO____

1.16 Se realizan análisis químicos del agua de la caldera? SI ____ NO____

1.17 Posee documentación técnica? SI_____ NO____

1.18 Posee banco de prueba de quemadores? SI ____ NO____

1.19 Posee instrumentos de medición de los siguientes parámetros

Temperatura de los Gases a la salida __ Temperatura del Agua de alimentación ___ Temperatura del Vapor ___

Flujo de Vapor ___ Presión del Vapor ___ Flujo de Combustible ___

1.20 Magnetizador para el H_2O de Alimentación ____ Emulsor de Combustible____

2- INSPECCION VISUAL DE LA CALDERA

2.1 Compruebe el estado técnico del refractario t _____°C

y del aislamiento térmico, la temperatura de las paredes exteriores no debe exceder de los 50 °C.

2.2 Revise el color de la llama, este debe ser uniforme y anaranjado.	Amarillo brillante __ Anaranjado __ Rojizo __
2.3 Verifique el funcionamiento libre de las compuertas de regulación de aire.	Funciona Bien __ Funciona Regular __ Funciona Mal __
2.4 Compruebe la hermeticidad de las mirillas y registros de acceso.	Buena __ Regular __ Mala __
2.5 Compruebe el funcionamiento de los niveles visuales de agua.	Funcionamiento __ No funciona __
2.6 Compruebe si las válvulas de seguridad del domo principal funcionan libremente.	SI __ NO __
2.7 Compruebe si los sistemas de regulación automática funcionan.	Totalmente __ Parcialmente __ No Funciona __
2.9 Chequear si se recuperan las purgas mediante sistema de Flash.	SI __ NO __
2.10 Compruebe si los sistemas de protección funcionan.	Bien __ Regular __ Mal __
2.11 Compruebe si los ventiladores de tiro forzado e inducido tienen ruido y/o vibraciones.	**VTF** **VTI** SI __ NO __ SI __ NO __
2.12 Chequee si tiene salideros de vapor.	SI __ NO __
2.13 Chequee si existe salideros de agua.	SI __ NO __
2.14 Compruebe si el operador conoce el valor de los principales parámetros de trabajo. (Todos los del modelo GV-3)	Totalmente __ Parcialmente __
2.15 Compruebe si existe el libro de control de los parámetros de trabajo diariamente	SI __ NO __
2.16 Verifique si existen Plan de Mantenimiento y su cumplimiento.	Existe y se cumple __ Existe y se viola __ No existe __

3- PARAMETROS DE LA CALDERA

		Valor Nominal	Valor Real	Uni-dades	Método Obtenc.
3.1	Producción de vapor.			t/h	Medición
3.2	Temp. de vapor entregado.			°C	Medición
3.3	Presión del vapor entregado.			kg/cm²	"
3.4	Temp. del agua de alimentar.			°C	"
	Presión del agua de alimentar			kg/cm²	"
3.5	Temp. del combustible.			°C	"
	Presión del combustible			kg/cm²	"
3.6	Temp. gases de salida.			°C	"
3.7	Temp. aire entrada del horno.			°C	"
3.8	Exceso de aire a la salida.			-	Cálculo
3.9	Consumo de combustible.			kg/h	Medición
3.10	Indice Bacharach.			-	Medición
3.11	CO_2 en gases escape.			%	"
3.12	O_2 en gases escape.			%	"
3.13	CO en gases escape.			%	"
3.14	% de purgas.			%	Estimado
3.15	Caudal agua alimentar			kg/h	Medición
3.16	Sólidos totales en el agua de la caldera.			ppm	Medición
3.17	Rendimiento térmico.			%	Cálculo
3.18	Ind.generac. bruta.			kg/kg	Cálculo
3.19	Humedad del bagazo.			%	Medición
3.20	Contenido de sacarosa del bagazo.			%	Medición

		Valor Nominal	Valor Real	Uni-dades	Método Obtenc.
3.21	Temperatura ambiente.			°C	"
3.22	Temperatura de las cenizas.			°C	"
3.23	Temperatura media de la pared.			°C	"
3.24	Diámetro de la caldera. Longitud de la caldera.			m m	" "
3.25	Poder Calórico Inferior.			kcal/kg	Calculado o por datos
3.26	Sólidos totales en el agua de alimentar a la caldera.			ppm	Medición
3.27	Costo del combustible.			USD/t	Datos

BALANCE ENERGETICO DE LA CALDERA

Generador de Vapor No. _____

ENERGIA DE ENTRADA (kcal/kg)

	CONCEPTO	**VALOR (kcal/kg)**	**%**
1	Poder calórico inferior	_____	_____
2	Calor de calentamiento del combustible	_____	_____
3	Calor aportado por el aire precalentado	_____	_____
4	Calor aportado por el vapor de atomización	_____	_____
5	Total	_____	**100**

ENERGIAS DE SALIDAS (kcal/kg)

	CONCEPTO	**VALOR (kcal/kg)**	**%**
1	Pérdida por Calor sensible en los gases	_____	_____
2	Pérdida por CO en gases	_____	_____
3	Pérdida por incombustión mecánica	_____	_____
4	Pérdida por radiación y convección	_____	_____
5	Otras	_____	_____
6	Calor útil	_____	_____
7	Suma total	_____	_____

NOTA: En el balance de la energía de salida la columna de % es con respecto a la energía de entrada.

1.- EVALUACION DE PÉRDIDAS

1- PERDIDAS POR ORIFICIOS Y VENTEOS

DATOS NECESARIOS

1.1.1 **SALIDEROS DE VAPOR DETECTADOS**

DIAMETRO DEL SALIDERO EN mm	**CANTIDAD DE SALIDEROS**	**PRESION DEL VAPOR EN kg/cm²**

1.1.2 Cálculos (Utilice el anexo 1).

1.1.3 Pérdidas de vapor: _____kg/h

1.1.4 Pérdidas de vapor: _____kg/h

1.1.5 Pérdidas de vapor: _____kg/h

1.1.6 Total de pérdidas: _____kg/h

1.1.7 Cálculo: (1/Indice de generación) x Factor 1.1.6 = kg Combustible/h

1.2 PERDIDAS DE CALOR POR AISLAMIENTO DE TUBERIAS DATOS NECESARIOS

- Si la tubería no tiene aislamiento térmico y no conoce la temperatura de su superficie.

2.1.1 **TUBERIAS SIN AISLAR**

Diámetro exterior (mm)	**Longitud tubería (m)**	**Presión fluido (kg/cm²)**	**Temperatura fluido (°C)**	**Horas de trabajo (h/año)**	**Cantidad de accesorios**	**Temperatura pared exterior de la tubería (°C)**

1.2.2 Cálculo (utilice el Anexo 2) en todos los casos.

1.2.3 Resultado: _____kg de fuel oil/año.

- Si es un tanque y no tiene aislamiento térmico necesitará:

1.2.4 **TANQUES SIN AISLAR (SIN AISLAMIENTO)**

Tanque No.	**Temperatura fluido interior (°C)**	**Longitud o altura (m)**	**Diámetro exterior (m)**	**Horas de trabajo en el año**

1.2.5 Si el recipiente no es cilíndrico, tome las dimensiones necesarias para el cálculo de la superficie exterior y datos
de 1.2.4.

1.2.6 Resultados: _____kg fuel/año.

1.3 **PERDIDAS POR NO RECUPERACION DEL CONDENSADO**

DATOS NECESARIOS

1.3.1 % condensado perdido de la producción de vapor. Cálculo (utilice gráfico del Anexo 3).

1.3.2 Resultados: ____% de incremento del consumo fuel oil

1.3.3 Calcule: (línea 1.3.2)(Consumo Fuel/año)/100= _____kg Fuel/año

1.4 **PERDIDAS DE COMBUSTIBLE POR BAJA TEMPERATURA DEL AGUA DE ALIMENTAR**

Por cada 5 °C menos que tenga el agua de alimentar en relación la que deba tener, estime un 1% de incremento
en el consumo de combustible respecto al nominal.

1.4.1 Temperatura Nominal del agua de alimentación - Temperatura Real = _____°C

1.4.2 Resultados:_____% de incremento del consumo de fuel oil.

1.4.3 Calcule: [(línea 1.4.2)/100](consumo fuel al año) = kg/año

1.5 **PERDIDAS POR NO AJUSTE DE LA SALINIDAD EN LA CALDERA**

1.4.1 Masa de vapor producido (M_v)

Datos en 3.1 del modelo GV - 3 y 1.7 del modelo GV - 1

M_v = {(kg vapor/h)(h/día)(día/semana)(semanas/año)]/año}/1000 t

1.4.2 Por ciento de purga requerido

Datos en 3.16 y 3.26 del MODELO GV - 3

% de purga requerido = [STD agua alimen./(STD caldera - STD agua de alimentación)]100

1.4.3 Fijar que valor de salinidad debemos recomendar alcanzar mediante un mejor control de las purgas y en correspondencia con los valores especificados en la norma UNE-9075. (ver ANEXO 5).

1.4.4 Por ciento de purga ajustada

% de purga requerido = [STD agua de alimentación/(STD recomendado - STD agua de alimentación)]100

1.4.5 Disminución del por ciento de purga

Ä P = % de purga requerido - % de purga ajustado

1.4.6 Disminución de la masa de purga (Ä M_p)

Ä M_p = M_v Ä P t/año

1.4.7 Se determina la entalpía del agua a la presión de trabajo de la caldera (i_A en kcal/kg).

1.4.8 Determinación de sobreconsumo de combustible

F = (Ä M_v i_A)/η VCI kg/año

1.4.9 Disminución de los costos de combustibles

(F)(precio del combustible) = USD/año

INSPECCION ESTATAL ENERGETICA			MODELO H - 1
RENDIMIENTO TERMICO DEL HORNO			
	DATOS NECESARIOS PARA EL CALCULO	**VALOR**	**U/M**
1.1	Tipo de horno		
1.2	Combustible que quema		
1.3	Consumo de combustible		ℓ/h
1.4	Longitud del horno		m
1.5	Ancho del horno		m
1.6	Temperatura de salida de los gases de escape		°C
1.7	Temperatura de salida de la carga del horno		°C
1.8	Temperatura de entrada de la carga al horno		°C
1.9	Carga alimentada al horno		kg/h
1.10	Volumen de aire introducido al horno		m^3/h
1.11	Temperatura entrada del aire al precalentador de aire		°C
1.12	Temperatura de salida del aire del precalentador de aire		°C
1.13	Poder calórico superior del combustible		kcal/kg
1.14	Poder calórico inferior del combustible		kcal/kg
1.15	Contenido de CO_2 en los gases de escape		%
1.16	Contenido de O_2 en los gases de escape		%
1.17	Calor especifico de la carga a la temperatura que tenga		kcal/kg.°C
1.18	Rendimiento Nominal del horno		%
	Resultados (los principales son los siguientes)		
1.19	Rendimiento térmico del horno		%
1.20	Pérdidas no medidas		kcal/h
1.21	Pérdidas con los gases de salida		kcal/h
1.22	Pérdidas totales		kcal/h
1.23	Calor absorbido por la carga		kcal/h
1.24	Sobreconsumo de combustible para baja eficiencia		t/período

ANEXO A

ANEXO B

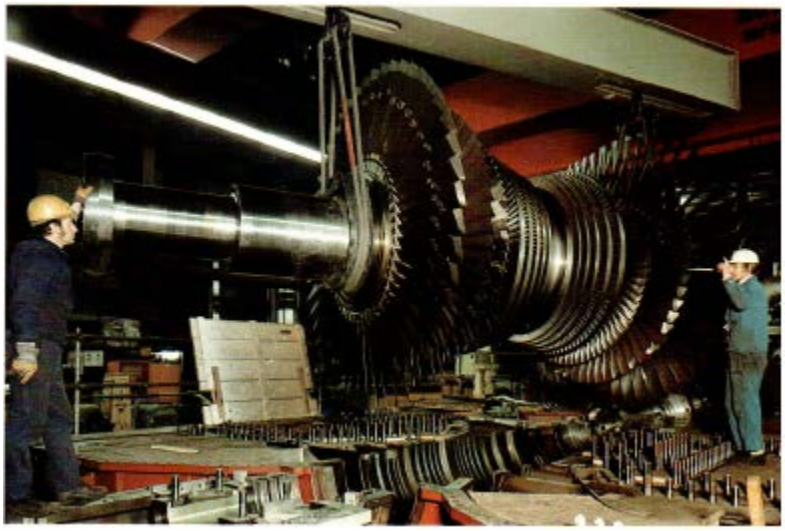


Figura B.1 Ensamblaje del rotor

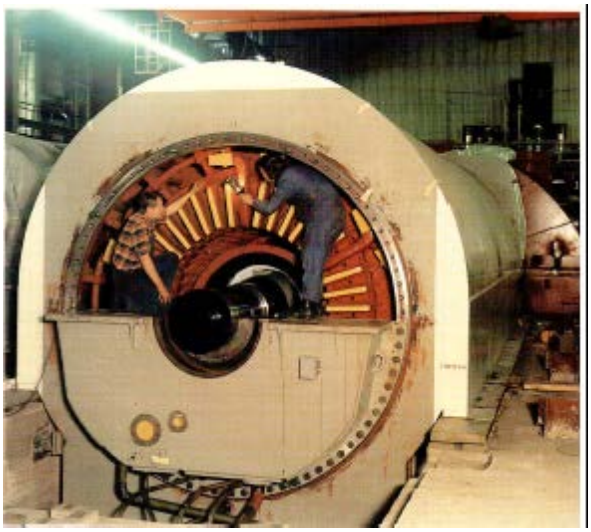


Figura B.2 Ensamblaje del generador

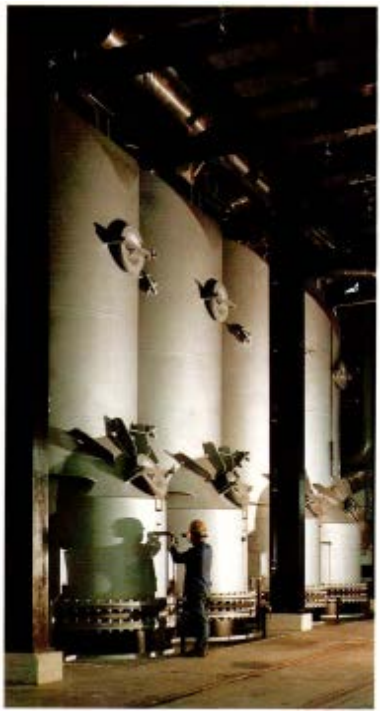


Figura B.3 Unidades de condensadores

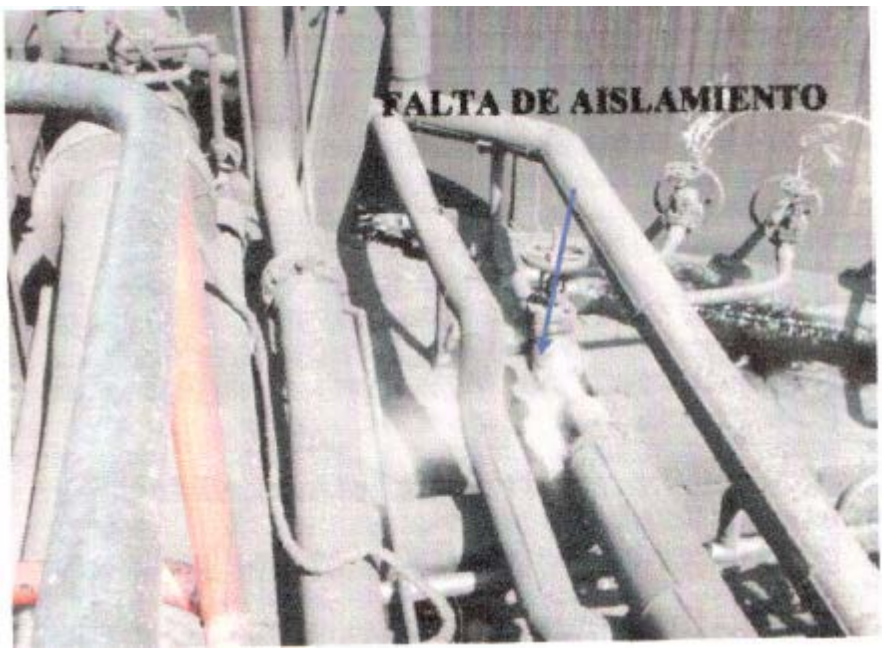


Figura B.4 Falta de aislamientos en sistema de vapor de trazas

Figura B.5 Falta de Aislamiento en las Válvulas

Figura B.6 Falta de Aislamientos en Tuberías

Figura B.7 Falta de Aislamientos en Tuberías

Figura B.8 Ventiladores de recirculación

Figura B.9 Ventiladores de recirculación

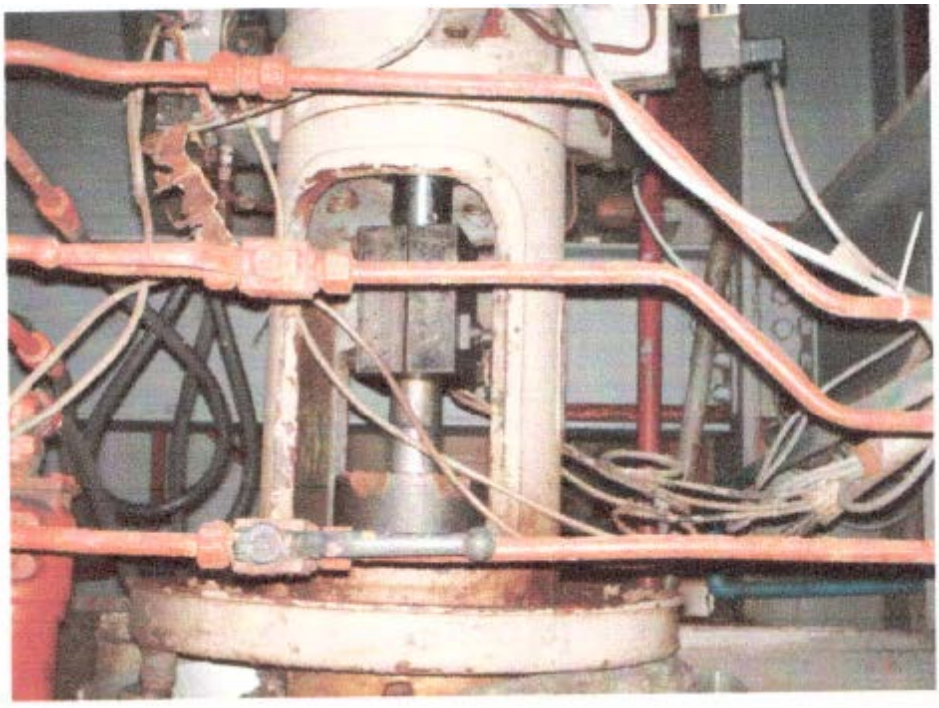


Figura B.10 By-pass de Alta Presión

Figura B.11 Tubería de succión agua de Mar

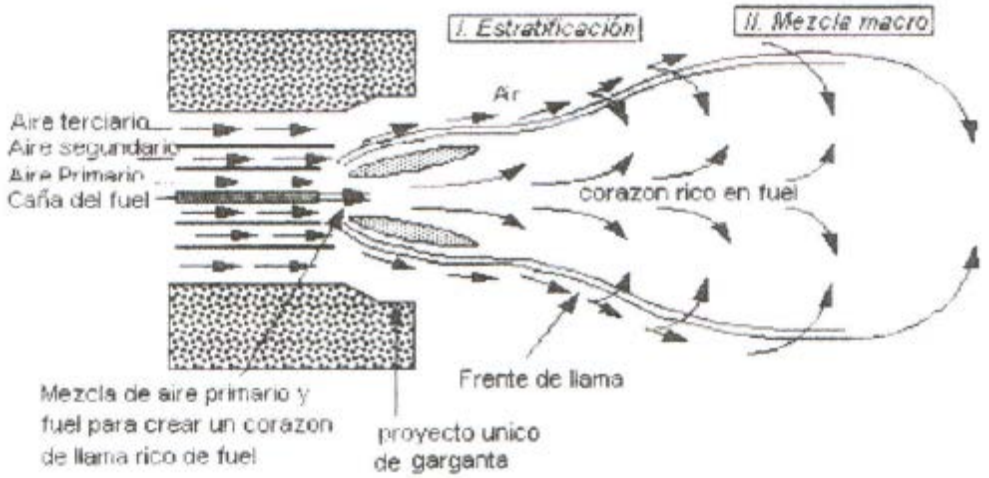


Figura B.12 Campo típico de flujos de aire y combustible

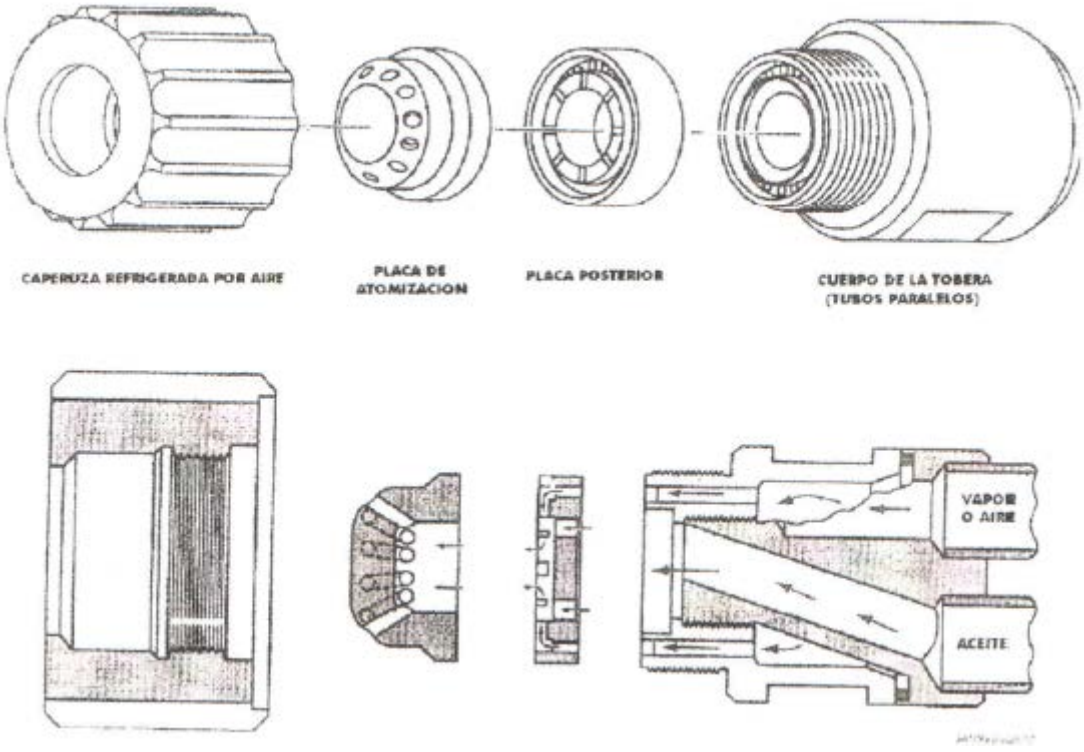


Figura B.13 Piezas de Atomización para la punta de Tobera

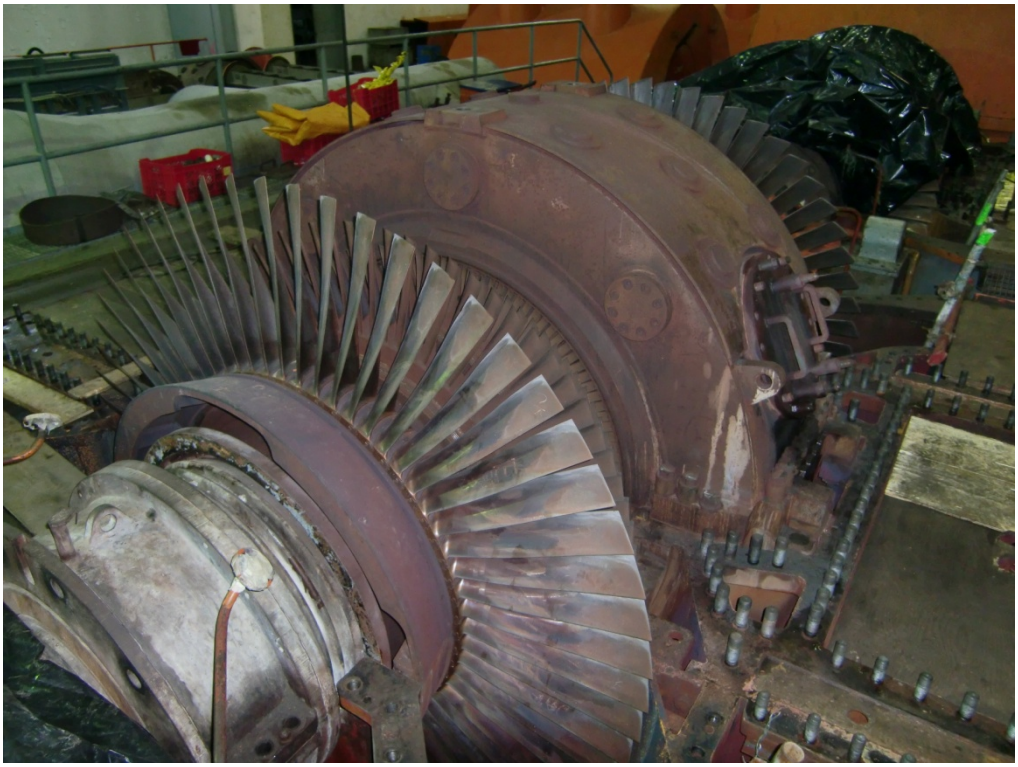


Figura B.14 Álabes de la Turbina

ANEXO D

TABLA A.1SI *Propiedades termodinámicas del agua (unidades SI)*
TABLA A.1.1SI *Agua saturada: tabla de temperatura (unidades SI)*

		Volumen específico, m^3/kg		Energía interna, kJ/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
Temp. °C T	Presión kPa, MPa P	Líquido saturado v_f	Vapor saturado v_g	Líquido saturado u_f	Evap. u_{fg}	Vapor saturado u_g	Líquido saturado h_f	Evap. h_{fg}	Vapor saturado h_g	Líquido saturado s_f	Evap. s_{fg}	Vapor saturado s_g
0.01	0.6113	0.001000	206.132	0.00	2375.3	2375.3	0.00	2501.3	2501.3	0.0000	9.1562	9.1562
5	0.8721	0.001000	147.118	20.97	2361.3	2382.2	20.98	2489.6	2510.5	0.0761	8.9496	9.0257
10	1.2276	0.001000	106.377	41.99	2347.2	2389.2	41.99	2477.7	2519.7	0.1510	8.7498	8.9007
15	1.7051	0.001001	77.925	62.98	2333.1	2396.0	62.98	2465.9	2528.9	0.2245	8.5569	8.7813
20	2.3385	0.001002	57.790	83.94	2319.0	2402.9	83.94	2454.1	2538.1	0.2966	8.3706	8.6671
25	3.1691	0.001003	43.359	104.86	2304.9	2409.8	104.87	2442.3	2547.2	0.3673	8.1905	8.5579
30	4.2461	0.001004	32.893	125.77	2290.8	2416.6	125.77	2430.5	2556.2	0.4369	8.0164	8.4533
35	5.6280	0.001006	25.216	146.65	2276.7	2423.4	146.66	2418.6	2565.3	0.5052	7.8478	8.3530
40	7.3837	0.001008	19.523	167.53	2262.6	2430.1	167.54	2406.7	2574.3	0.5724	7.6845	8.2569
45	9.5934	0.001010	15.258	188.41	2248.4	2436.8	188.42	2394.8	2583.2	0.6386	7.5261	8.1647
50	12.350	0.001012	12.032	209.30	2234.2	2443.5	209.31	2382.7	2592.1	0.7037	7.3725	8.0762
55	15.758	0.001015	9.568	230.19	2219.9	2450.1	230.20	2370.7	2600.9	0.7679	7.2234	7.9912
60	19.941	0.001017	7.671	251.09	2205.5	2456.6	251.11	2358.5	2609.6	0.8311	7.0784	7.9095
65	25.033	0.001020	6.197	272.00	2191.1	2463.1	272.03	2346.2	2618.2	0.8934	6.9375	7.8309
70	31.188	0.001023	5.042	292.93	2176.6	2469.5	292.96	2333.8	2626.8	0.9548	6.8004	7.7552
75	38.578	0.001026	4.131	313.87	2162.0	2475.9	313.91	2321.4	2635.3	1.0154	6.6670	7.6824
80	47.390	0.001029	3.407	334.84	2147.4	2482.2	334.88	2308.8	2643.7	1.0752	6.5369	7.6121
85	57.834	0.001032	2.828	355.82	2132.6	2488.4	355.88	2296.0	2651.9	1.1342	6.4102	7.5444
90	70.139	0.001036	2.361	376.82	2117.7	2494.5	376.90	2283.2	2660.1	1.1924	6.2866	7.4790
95	84.554	0.001040	1.982	397.86	2102.7	2500.6	397.94	2270.2	2668.1	1.2500	6.1659	7.4158
100	101.325	0.001044	1.6729	418.91	2087.6	2506.5	419.02	2257.0	2676.0	1.3068	6.0480	7.3548

TABLA A.1SI (Continuación) *Propiedades termodinámicas del agua (unidades SI)*
TABLA A.1.1SI *Agua saturada: tabla de temperatura (unidades SI)*

		Volumen específico, m^3/kg		Energía interna, kJ/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
Temp. °C T	Presión Mpa P	Líquido saturado v_f	Vapor saturado v_g	Líquido saturado u_f	Evap. u_{fg}	Vapor saturado u_g	Líquido saturado h_f	Evap. h_{fg}	Vapor saturado h_g	Líquido saturado s_f	Evap. s_{fg}	Vapor saturado s_g
105	0.12082	0.001047	1.4194	440.00	2072.3	2512.3	440.13	2243.7	2683.8	1.3629	5.9328	7.2958
110	0.14328	0.001052	1.2102	461.12	2057.0	2518.1	461.27	2230.2	2691.5	1.4184	5.8202	7.2386
115	0.16906	0.001056	1.0366	482.28	2041.4	2523.7	482.46	2216.5	2699.0	1.4733	5.7100	7.1832
120	0.19853	0.001060	0.8919	503.48	2025.8	2529.2	503.69	2202.6	2706.3	1.5275	5.6020	7.1295
125	0.2321	0.001065	0.77059	524.72	2009.9	2534.6	524.96	2188.5	2713.5	1.5812	5.4962	7.0774
130	0.2701	0.001070	0.66850	546.00	1993.9	2539.9	546.29	2174.2	2720.5	1.6343	5.3925	7.0269
135	0.3130	0.001075	0.58217	567.34	1977.7	2545.0	567.67	2159.6	2727.3	1.6869	5.2907	6.9777
140	0.3613	0.001080	0.50885	588.72	1961.3	2550.0	589.11	2144.8	2733.9	1.7390	5.1908	6.9298
145	0.4154	0.001085	0.44632	610.16	1944.7	2554.9	610.61	2129.6	2740.3	1.7906	5.0926	6.8832
150	0.4759	0.001090	0.39278	631.66	1927.9	2559.5	632.18	2114.3	2746.4	1.8417	4.9960	6.8378
155	0.5431	0.001096	0.34676	653.23	1910.8	2564.0	653.82	2098.6	2752.4	1.8924	4.9010	6.7934
160	0.6178	0.001102	0.30706	674.85	1893.5	2568.4	675.53	2082.6	2758.1	1.9426	4.8075	6.7501
165	0.7005	0.001108	0.27269	696.55	1876.0	2572.5	697.32	2066.2	2763.5	1.9924	4.7153	6.7078
170	0.7917	0.001114	0.24283	718.31	1858.1	2576.5	719.20	2049.5	2768.7	2.0418	4.6244	6.6663
175	0.8920	0.001121	0.21680	740.16	1840.0	2580.2	741.16	2032.4	2773.6	2.0909	4.5347	6.6256
180	1.0022	0.001127	0.19405	762.08	1821.6	2583.7	763.21	2015.0	2778.2	2.1395	4.4461	6.5857
185	1.1227	0.001134	0.17409	784.08	1802.9	2587.0	785.36	1997.1	2782.4	2.1878	4.3586	6.5464
190	1.2544	0.001141	0.15654	806.17	1783.8	2590.0	807.61	1978.8	2786.4	2.2358	4.2720	6.5078
195	1.3978	0.001149	0.14105	828.36	1764.4	2592.8	829.96	1960.0	2790.0	2.2835	4.1863	6.4697
200	1.5538	0.001156	0.12736	850.64	1744.7	2595.3	852.43	1940.7	2793.2	2.3308	4.1014	6.4322
205	1.7230	0.001164	0.11521	873.02	1724.5	2597.5	875.03	1921.0	2796.0	2.3779	4.0172	6.3951
210	1.9063	0.001173	0.10441	895.51	1703.9	2599.4	897.75	1900.7	2798.5	2.4247	3.9337	6.3584
215	2.1042	0.001181	0.09479	918.12	1682.9	2601.1	920.61	1879.9	2800.5	2.4713	3.8507	6.3221
220	2.3178	0.001190	0.08619	940.85	1661.5	2602.3	943.61	1858.5	2802.1	2.5177	3.7683	6.2860

		Volumen específico, m^3/kg		Energía interna, kJ/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
Temp. °C T	Presión Mpa P	Líquido saturado v_f	Vapor saturado v_g	Líquido saturado u_f	Evap. u_{fg}	Vapor saturado u_g	Líquido saturado h_f	Evap. h_{fg}	Vapor saturado h_g	Líquido saturado s_f	Evap. s_{fg}	Vapor saturado s_g
225	2.5477	0.001199	0.07849	963.72	1639.6	2603.3	966.77	1836.5	2803.3	2.5639	3.6863	6.2502
230	2.7949	0.001209	0.07158	986.72	1617.2	2603.9	990.10	1813.8	2803.9	2.6099	3.6047	6.2146
235	3.0601	0.001219	0.06536	1009.88	1594.2	2604.1	1013.61	1790.5	2804.1	2.6557	3.5233	6.1791
240	3.3442	0.001229	0.05976	1033.19	1570.8	2603.9	1037.31	1766.5	2803.8	2.7015	3.4422	6.1436
245	3.6482	0.001240	0.05470	1056.69	1546.7	2603.4	1061.21	1741.7	2802.9	2.7471	3.3612	6.1083
250	3.9730	0.001251	0.05013	1080.37	1522.0	2602.4	1085.34	1716.2	2801.5	2.7927	3.2802	6.0729
255	4.3195	0.001263	0.04598	1104.26	1496.7	2600.9	1109.72	1689.8	2799.5	2.8382	3.1992	6.0374
260	4.6886	0.001276	0.04220	1128.37	1470.6	2599.0	1134.35	1662.5	2796.9	2.8837	3.1181	6.0018
265	5.0813	0.001289	0.03877	1152.72	1443.9	2596.6	1159.27	1634.3	2793.6	2.9293	3.0368	5.9661
270	5.4987	0.001302	0.03564	1177.33	1416.3	2593.7	1184.49	1605.2	2789.7	2.9750	2.9551	5.9301
275	5.9418	0.001317	0.03279	1202.23	1387.9	2590.2	1210.05	1574.9	2785.0	3.0208	2.8730	5.8937
280	6.4117	0.001332	0.03017	1227.43	1358.7	2586.1	1235.97	1543.6	2779.5	3.0667	2.7903	5.8570
285	6.9094	0.001348	0.02777	1252.98	1328.4	2581.4	1262.29	1511.0	2773.3	3.1129	2.7069	5.8198
290	7.4360	0.001366	0.02557	1278.89	1297.1	2576.0	1289.04	1477.1	2766.1	3.1593	2.6227	5.7821
295	7.9928	0.001384	0.02354	1305.21	1264.7	2569.9	1316.27	1441.8	2758.0	3.2061	2.5375	5.7436
300	8.5810	0.001404	0.02167	1331.97	1231.0	2563.0	1344.01	1404.9	2748.9	3.2533	2.4511	5.7044
305	9.2018	0.001425	0.01995	1359.22	1195.9	2555.2	1372.33	1366.4	2738.7	3.3009	2.3633	5.6642
310	9.8566	0.001447	0.01835	1387.03	1159.4	2546.4	1401.29	1326.0	2727.3	3.3492	2.2737	5.6229
315	10.547	0.001472	0.01687	1415.44	1121.1	2536.6	1430.97	1283.5	2714.4	3.3981	2.1821	5.5803
320	11.274	0.001499	0.01549	1444.55	1080.9	2525.5	1461.45	1238.6	2700.1	3.4479	2.0882	5.5361
330	12.845	0.001561	0.012996	1505.24	993.7	2498.9	1525.29	1140.6	2665.8	3.5506	1.8909	5.4416
340	14.586	0.001638	0.010797	1570.26	894.3	2464.5	1594.15	1027.9	2622.0	3.6593	1.6763	5.3356
350	16.514	0.001740	0.008813	1641.81	776.6	2418.4	1670.54	893.4	2563.9	3.7776	1.4336	5.2111
360	18.651	0.001892	0.006945	1725.19	626.3	2351.5	1760.48	720.5	2481.0	3.9146	1.1379	5.0525
370	21.028	0.002213	0.004926	1843.84	384.7	2228.5	1890.37	441.8	2332.1	4.1104	0.6868	4.7972
374.14	22.089	0.003155	0.003155	2029.58	0	2029.6	2099.26	0	2099.3	4.4297	0	4.4297

TABLA A.1.2SI *Agua saturada: tabla de presión (unidades SI)*

Presión kPa P	Temp. °C T	Volumen específico, m³/kg: Líquido saturado v_f	Volumen específico, m³/kg: Vapor saturado v_g	Energía interna, kJ/kg: Líquido saturado u_f	Energía interna, kJ/kg: Evap. u_{fg}	Energía interna, kJ/kg: Vapor saturado u_g	Entalpía, kJ/kg: Líquido saturado h_f	Entalpía, kJ/kg: Evap. h_{fg}	Entalpía, kJ/kg: Vapor saturado h_g	Entropía, kJ/kg K: Líquido saturado s_f	Entropía, kJ/kg K: Evap. s_{fg}	Entropía, kJ/kg K: Vapor saturado s_g
0.6113	0.01	0.001000	206.132	0	2375.3	2375.3	0.00	2501.3	2501.3	0	9.1562	9.1562
1.0	6.98	0.001000	129.208	29.29	2355.7	2385.0	29.29	2484.9	2514.2	0.1059	8.8697	8.9756
1.5	13.03	0.001001	87.980	54.70	2338.6	2393.3	54.70	2470.6	2525.3	0.1956	8.6322	8.8278
2.0	17.50	0.001001	67.004	73.47	2326.0	2399.5	73.47	2460.0	2533.5	0.2607	8.4629	8.7236
2.5	21.08	0.001002	54.254	88.47	2315.9	2404.4	88.47	2451.6	2540.0	0.3120	8.3311	8.6431
3.0	24.08	0.001003	45.665	101.03	2307.5	2408.5	101.03	2444.5	2545.5	0.3545	8.2231	8.5775
4.0	28.96	0.001004	34.800	121.44	2293.7	2415.2	121.44	2432.9	2554.4	0.4226	8.0520	8.4746
5.0	32.88	0.001005	28.193	137.79	2282.7	2420.5	137.79	2423.7	2561.4	0.4763	7.9187	8.3950
7.5	40.29	0.001008	19.238	168.76	2261.7	2430.5	168.77	2406.0	2574.8	0.5763	7.6751	8.2514
10.0	45.81	0.001010	14.674	191.79	2246.1	2437.9	191.81	2392.8	2584.6	0.6492	7.5010	8.1501
15.0	53.97	0.001014	10.022	225.90	2222.8	2448.7	225.91	2373.1	2599.1	0.7548	7.2536	8.0084
20.0	60.06	0.001017	7.649	251.35	2205.4	2456.7	251.38	2358.3	2609.7	0.8319	7.0766	7.9085
25.0	64.97	0.001020	6.204	271.88	2191.2	2463.1	271.90	2346.3	2618.2	0.8930	6.9383	7.8313
30.0	69.10	0.001022	5.229	289.18	2179.2	2468.4	289.21	2336.1	2625.3	0.9439	6.8247	7.7686
40.0	75.87	0.001026	3.993	317.51	2159.5	2477.0	317.55	2319.2	2636.7	1.0258	6.6441	7.6700
50.0	81.33	0.001030	3.240	340.42	2143.4	2483.8	340.47	2305.4	2645.9	1.0910	6.5029	7.5939
75.0	91.77	0.001037	2.217	384.29	2112.4	2496.7	384.36	2278.6	2663.0	1.2129	6.2434	7.4563
MPa												
0.100	99.62	0.001043	1.6940	417.33	2088.7	2506.1	417.44	2258.0	2675.5	1.3025	6.0568	7.3593
0.125	105.99	0.001048	1.3749	444.16	2069.3	2513.5	444.30	2241.1	2685.3	1.3739	5.9104	7.2843
0.150	111.37	0.001053	1.1593	466.92	2052.7	2519.6	467.08	2226.5	2693.5	1.4335	5.7897	7.2232
0.175	116.06	0.001057	1.0036	486.78	2038.1	2524.9	486.97	2213.6	2700.5	1.4848	5.6868	7.1717
0.200	120.23	0.001061	0.8857	504.47	2025.0	2529.5	504.68	2202.0	2706.6	1.5300	5.5970	7.1271
0.225	124.00	0.001064	0.7933	520.45	2013.1	2533.6	520.69	2191.3	2712.0	1.5705	5.5173	7.0878
0.250	127.43	0.001067	0.7187	535.08	2002.1	2537.2	535.34	2181.5	2716.9	1.6072	5.4455	7.0526

Presión MPa P	Temp. °C T	Volumen específico, m³/kg: Líquido saturado v_f	Volumen específico, m³/kg: Vapor saturado v_g	Energía interna, kJ/kg: Líquido saturado u_f	Energía interna, kJ/kg: Evap. u_{fg}	Energía interna, kJ/kg: Vapor saturado u_g	Entalpía, kJ/kg: Líquido saturado h_f	Entalpía, kJ/kg: Evap. h_{fg}	Entalpía, kJ/kg: Vapor saturado h_g	Entropía, kJ/kg K: Líquido saturado s_f	Entropía, kJ/kg K: Evap. s_{fg}	Entropía, kJ/kg K: Vapor saturado s_g
0.275	130.60	0.001070	0.6573	548.57	1992.0	2540.5	548.87	2172.4	2721.3	1.6407	5.3801	7.0208
0.300	133.55	0.001073	0.6058	561.13	1982.4	2543.6	561.45	2163.9	2725.3	1.6717	5.3201	6.9918
0.325	136.30	0.001076	0.5620	572.88	1973.5	2546.3	573.23	2155.8	2729.0	1.7005	5.2646	6.9651
0.350	138.88	0.001079	0.5243	583.93	1965.0	2548.9	584.31	2148.1	2732.4	1.7274	5.2130	6.9404
0.375	141.32	0.001081	0.4914	594.38	1956.9	2551.3	594.79	2140.8	2735.6	1.7527	5.1647	6.9174
0.40	143.63	0.001084	0.4625	604.29	1949.3	2553.6	604.73	2133.8	2738.5	1.7766	5.1193	6.8958
0.45	147.93	0.001088	0.4140	622.75	1934.9	2557.6	623.24	2120.7	2743.9	1.8206	5.0359	6.8565
0.50	151.86	0.001093	0.3749	639.66	1921.6	2561.2	640.21	2108.5	2748.7	1.8606	4.9606	6.8212
0.55	155.48	0.001097	0.3427	655.30	1909.2	2564.5	655.91	2097.0	2752.9	1.8972	4.8920	6.7892
0.60	158.85	0.001101	0.3157	669.88	1897.5	2567.4	670.54	2086.3	2756.8	1.9311	4.8289	6.7600
0.65	162.01	0.001104	0.2927	683.55	1886.5	2570.1	684.26	2076.0	2760.3	1.9627	4.7704	6.7330
0.70	164.97	0.001108	0.2729	696.43	1876.1	2572.5	697.20	2066.3	2763.5	1.9922	4.7158	6.7080
0.75	167.77	0.001111	0.2556	708.62	1866.1	2574.7	709.45	2057.0	2766.4	2.0199	4.6647	6.6846
0.80	170.43	0.001115	0.2404	720.20	1856.6	2576.8	721.10	2048.0	2769.1	2.0461	4.6166	6.6627
0.85	172.96	0.001118	0.2270	731.25	1847.4	2578.7	732.20	2039.4	2771.6	2.0709	4.5711	6.6421
0.90	175.38	0.001121	0.2150	741.81	1838.7	2580.5	742.82	2031.1	2773.9	2.0946	4.5280	6.6225
0.95	177.69	0.001124	0.2042	751.94	1830.2	2582.1	753.00	2023.1	2776.1	2.1171	4.4869	6.6040
1.00	179.91	0.001127	0.19444	761.67	1822.0	2583.6	762.79	2015.3	2778.1	2.1386	4.4478	6.5864
1.10	184.09	0.001133	0.17753	780.08	1806.3	2586.4	781.32	2000.4	2781.7	2.1791	4.3744	6.5535
1.20	187.99	0.001139	0.16333	797.27	1791.6	2588.8	798.64	1986.2	2784.8	2.2165	4.3067	6.5233
1.30	191.64	0.001144	0.15125	813.42	1777.5	2590.9	814.91	1972.7	2787.6	2.2514	4.2438	6.4953
1.40	195.07	0.001149	0.14084	828.68	1764.1	2592.8	830.29	1959.7	2790.0	2.2842	4.1850	6.4692
1.50	198.32	0.001154	0.13177	843.14	1751.3	2594.5	844.87	1947.3	2792.1	2.3150	4.1298	6.4448
1.75	205.76	0.001166	0.11349	876.44	1721.4	2597.8	878.48	1918.0	2796.4	2.3851	4.0044	6.3895
2.00	212.42	0.001177	0.09963	906.42	1693.8	2600.3	908.77	1890.7	2799.5	2.4473	3.8935	6.3408
2.25	218.45	0.001187	0.08875	933.81	1668.2	2602.0	936.48	1865.2	2801.7	2.5034	3.7938	6.2971

TABLA A.1.2SI (Continuación) *Agua saturada: tabla de presión (unidades SI)*

		Volumen específico, m^3/kg		Energía interna, kJ/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
Presión MPa P	Temp. °C T	Líquido saturado v_f	Vapor saturado v_g	Líquido saturado u_f	Evap. u_{fg}	Vapor saturado u_g	Líquido saturado h_f	Evap. h_{fg}	Vapor saturado h_g	Líquido saturado s_f	Evap. s_{fg}	Vapor saturado s_g
2.50	223.99	0.001197	0.07998	959.09	1644.0	2603.1	962.09	1841.0	2803.1	2.5546	3.7028	6.2574
2.75	229.12	0.001207	0.07275	982.65	1621.2	2603.8	985.97	1817.9	2803.9	2.6018	3.6190	6.2208
3.00	233.90	0.001216	0.06668	1004.76	1599.3	2604.1	1008.41	1795.7	2804.1	2.6456	3.5412	6.1869
3.25	238.38	0.001226	0.06152	1025.62	1578.4	2604.0	1029.60	1774.4	2804.0	2.6866	3.4685	6.1551
3.50	242.60	0.001235	0.05707	1045.41	1558.3	2603.7	1049.73	1753.7	2803.4	2.7252	3.4000	6.1252
4.0	250.40	0.001252	0.049778	1082.28	1520.0	2602.3	1087.29	1714.1	2801.4	2.7963	3.2737	6.0700
5.0	263.99	0.001286	0.039441	1147.78	1449.3	2597.1	1154.21	1640.1	2794.3	2.9201	3.0532	5.9733
6.0	275.64	0.001319	0.032440	1205.41	1384.3	2589.7	1213.32	1571.0	2784.3	3.0266	2.8625	5.8891
7.0	285.88	0.001351	0.027370	1257.51	1323.0	2580.5	1266.97	1505.1	2772.1	3.1210	2.6922	5.8132
8.0	295.06	0.001384	0.023518	1305.54	1264.3	2569.8	1316.61	1441.3	2757.9	3.2067	2.5365	5.7431
9.0	303.40	0.001418	0.020484	1350.47	1207.3	2557.8	1363.23	1378.9	2742.1	3.2857	2.3915	5.6771
10.0	311.06	0.001452	0.018026	1393.00	1151.4	2544.4	1407.53	1317.1	2724.7	3.3595	2.2545	5.6140
11.0	318.15	0.001489	0.015987	1433.68	1096.1	2529.7	1450.05	1255.5	2705.6	3.4294	2.1233	5.5527
12.0	324.75	0.001527	0.014263	1472.92	1040.8	2513.7	1491.24	1193.6	2684.8	3.4961	1.9962	5.4923
13.0	330.93	0.001567	0.012780	1511.09	985.0	2496.1	1531.46	1130.8	2662.2	3.5604	1.8718	5.4323
14.0	336.75	0.001611	0.011485	1548.53	928.2	2476.8	1571.08	1066.5	2637.5	3.6231	1.7485	5.3716
15.0	342.24	0.001658	0.010338	1585.58	869.8	2455.4	1610.45	1000.0	2610.5	3.6847	1.6250	5.3097
16.0	347.43	0.001711	0.009306	1622.63	809.1	2431.7	1650.00	930.6	2580.6	3.7460	1.4995	5.2454
17.0	352.37	0.001770	0.008365	1660.16	744.8	2405.0	1690.25	856.9	2547.2	3.8078	1.3698	5.1776
18.0	357.06	0.001840	0.007490	1698.86	675.4	2374.3	1731.97	777.1	2509.1	3.8713	1.2330	5.1044
19.0	361.54	0.001924	0.006657	1739.87	598.2	2338.1	1776.43	688.1	2464.5	3.9387	1.0841	5.0227
20.0	365.81	0.002035	0.005834	1785.47	507.6	2293.1	1826.18	583.6	2409.7	4.0137	0.9132	4.9269
21.0	369.89	0.002206	0.004953	1841.97	388.7	2230.7	1888.30	446.4	2334.7	4.1073	0.6942	4.8015
22.0	373.80	0.002808	0.003526	1973.16	108.2	2081.4	2034.92	124.0	2159.0	4.3307	0.1917	4.5224
22.09	374.14	0.003155	0.003155	2029.58	0	2029.6	2099.26	0	2099.3	4.4297	0	4.4297

TABLA A.1.3SI *Vapor de agua sobrecalentado (unidades SI)*

	P = 10 kPa (45.81)				P = 50 kPa (81.33)				P = 100 kPa (99.62)			
T	v	u	h	s	v	u	h	s	v	u	h	s
Sat.	14.674	2437.9	2584.6	8.1501	3.240	2483.8	2645.9	7.5939	1.6940	2506.1	2675.5	7.3593
50	14.869	2443.9	2592.6	8.1749	—	—	—	—	—	—	—	—
100	17.196	2515.5	2687.5	8.4479	3.418	2511.6	2682.5	7.6947	1.6958	2506.6	2676.2	7.3614
150	19.513	2587.9	2783.0	8.6881	3.889	2585.6	2780.1	7.9400	1.9364	2582.7	2776.4	7.6133
200	21.825	2661.3	2879.5	8.9037	4.356	2659.8	2877.6	8.1579	2.1723	2658.0	2875.3	7.8342
250	24.136	2736.0	2977.3	9.1002	4.821	2735.0	2976.0	8.3555	2.4060	2733.7	2974.3	8.0332
300	26.445	2812.1	3076.5	9.2812	5.284	2811.3	3075.5	8.5372	2.6388	2810.4	3074.3	8.2157
400	31.063	2968.9	3279.5	9.6076	6.209	2968.4	3278.9	8.8641	3.1026	2967.8	3278.1	8.5434
500	35.679	3132.3	3489.0	9.8977	7.134	3131.9	3488.6	9.1545	3.5655	3131.5	3488.1	8.8341
600	40.295	3302.5	3705.4	10.1608	8.058	3302.2	3705.1	9.4177	4.0278	3301.9	3704.7	9.0975
700	44.911	3479.6	3928.7	10.4028	8.981	3479.5	3928.5	9.6599	4.4899	3479.2	3928.2	9.3398
800	49.526	3663.8	4159.1	10.6281	9.904	3663.7	4158.9	9.8852	4.9517	3663.5	4158.7	9.5652
900	54.141	3855.0	4396.4	10.8395	10.828	3854.9	4396.3	10.0967	5.4135	3854.8	4396.1	9.7767
1000	58.757	4053.0	4640.6	11.0392	11.751	4052.9	4640.5	10.2964	5.8753	4052.8	4640.3	9.9764
1100	63.372	4257.5	4891.2	11.2287	12.674	4257.4	4891.1	10.4858	6.3370	4257.3	4890.9	10.1658
1200	67.987	4467.9	5147.8	11.4090	13.597	4467.8	5147.7	10.6662	6.7986	4467.7	5147.6	10.3462
1300	72.603	4683.7	5409.7	11.5810	14.521	4683.6	5409.6	10.8382	7.2603	4683.5	5409.5	10.5182
	P = 200 kPa (120.23)				P = 300 kPa (133.55)				P = 400 kPa (143.63)			
Sat.	0.88573	2529.5	2706.6	7.1271	0.60582	2543.6	2725.3	6.9918	0.46246	2553.6	2738.5	6.8958
150	0.95964	2576.9	2768.8	7.2795	0.63388	2570.8	2761.0	7.0778	0.47084	2564.5	2752.8	6.9299
200	1.08034	2654.4	2870.5	7.5066	0.71629	2650.7	2865.5	7.3115	0.53422	2646.8	2860.5	7.1706
250	1.19880	2731.2	2971.0	7.7085	0.79636	2728.7	2967.6	7.5165	0.59512	2726.1	2964.2	7.3788
300	1.31616	2808.6	3071.8	7.8926	0.87529	2806.7	3069.3	7.7022	0.65484	2804.8	3066.7	7.5661
400	1.54930	2966.7	3276.5	8.2217	1.03151	2965.5	3275.0	8.0329	0.77262	2964.4	3273.4	7.8984
500	1.78139	3130.7	3487.0	8.5132	1.18669	3130.0	3486.0	8.3250	0.88934	3129.2	3484.9	8.1912
600	2.01297	3301.4	3704.0	8.7769	1.34136	3300.8	3703.2	8.5892	1.00555	3300.2	3702.4	8.4557
700	2.24426	3478.8	3927.7	9.0194	1.49573	3478.4	3927.1	8.8319	1.12147	3477.9	3926.5	8.6987
800	2.47539	3663.2	4158.3	9.2450	1.64994	3662.9	4157.8	9.0575	1.23722	3662.5	4157.4	8.9244

TABLA A.1.3SI (Continuación) *Vapor de agua sobrecalentado (unidades SI)*

	P = 200 kPa (120.23)				P = 300 kPa (133.55)				P = 400 kPa (143.63)			
T	v	u	h	s	v	u	h	s	v	u	h	s
900	2.70643	3854.5	4395.8	9.4565	1.80406	3854.2	4395.4	9.2691	1.35288	3853.9	4395.1	9.1361
1000	2.93740	4052.5	4640.0	9.6563	1.95812	4052.3	4639.7	9.4689	1.46847	4052.0	4639.4	9.3360
1100	3.16834	4257.0	4890.7	9.8458	2.11214	4256.8	4890.4	9.6585	1.58404	4256.5	4890.1	9.5255
1200	3.39927	4467.5	5147.3	10.0262	2.26614	4467.2	5147.1	9.8389	1.69958	4467.0	5146.8	9.7059
1300	3.63018	4683.2	5409.3	10.1982	2.42013	4683.0	5409.0	10.0109	1.81511	4682.8	5408.8	9.8780
	P = 500 kPa (151.86)				P = 600 kPa (158.85)				P = 800 kPa (170.43)			
Sat.	0.37489	2561.2	2748.7	6.8212	0.31567	2567.4	2756.8	6.7600	0.24043	2576.8	2769.1	6.6627
200	0.42492	2642.9	2855.4	7.0592	0.35202	2638.9	2850.1	6.9665	0.26080	2630.6	2839.2	6.8158
250	0.47436	2723.5	2960.7	7.2708	0.39383	2720.9	2957.2	7.1816	0.29314	2715.5	2950.0	7.0384
300	0.52256	2802.9	3064.2	7.4598	0.43437	2801.0	3061.6	7.3723	0.32411	2797.1	3056.4	7.2327
350	0.57012	2882.6	3167.6	7.6328	0.47424	2881.1	3165.7	7.5463	0.35439	2878.2	3161.7	7.4088
400	0.61728	2963.2	3271.8	7.7937	0.51372	2962.0	3270.2	7.7078	0.38426	2959.7	3267.1	7.5715
500	0.71093	3128.4	3483.8	8.0872	0.59199	3127.6	3482.7	8.0020	0.44331	3125.9	3480.6	7.8672
600	0.80406	3299.6	3701.7	8.3521	0.66974	3299.1	3700.9	8.2673	0.50184	3297.9	3699.4	8.1332
700	0.89691	3477.5	3926.0	8.5952	0.74720	3477.1	3925.4	8.5107	0.56007	3476.2	3924.3	8.3770
800	0.98959	3662.2	4157.0	8.8211	0.82450	3661.8	4156.5	8.7367	0.61813	3661.1	4155.7	8.6033
900	1.08217	3853.6	4394.7	9.0329	0.90169	3853.3	4394.4	8.9485	0.67610	3852.8	4393.6	8.8153
1000	1.17469	4051.8	4639.1	9.2328	0.97883	4051.5	4638.8	9.1484	0.73401	4051.0	4638.2	9.0153
1100	1.26718	4256.3	4889.9	9.4224	1.05594	4256.1	4889.6	9.3381	0.79188	4255.6	4889.1	9.2049
1200	1.35964	4466.8	5146.6	9.6028	1.13302	4466.5	5146.3	9.5185	0.84974	4466.1	5145.8	9.3854
1300	1.45210	4682.5	5408.6	9.7749	1.21009	4682.3	5408.3	9.6906	0.90758	4681.8	5407.9	9.5575
	P = 1.00 MPa (179.91)				P = 1.20 MPa (187.99)				P = 1.40 MPa (195.07)			
Sat.	0.19444	2583.6	2778.1	6.5864	0.16333	2588.8	2784.8	6.5233	0.14084	2592.8	2790.0	6.4692
200	0.20596	2621.9	2827.9	6.6939	0.16930	2612.7	2815.9	6.5898	0.14302	2603.1	2803.3	6.4975
250	0.23268	2709.9	2942.6	6.9246	0.19235	2704.2	2935.0	6.8293	0.16350	2698.3	2927.2	6.7467
300	0.25794	2793.2	3051.2	7.1228	0.21382	2789.2	3045.8	7.0316	0.18228	2785.2	3040.4	6.9533
350	0.28247	2875.2	3157.7	7.3010	0.23452	2872.2	3153.6	7.2120	0.20026	2869.1	3149.5	7.1359
400	0.30659	2957.3	3263.9	7.4650	0.25480	2954.9	3260.7	7.3773	0.21780	2952.5	3257.4	7.3025
500	0.35411	3124.3	3478.4	7.7621	0.29463	3122.7	3476.3	7.6758	0.25215	3121.1	3474.1	7.6026

	P = 1.00 MPa (179.91)				P = 1.20 MPa (187.99)				P = 1.40 MPa (195.07)			
T	v	u	h	s	v	u	h	s	v	u	h	s
600	0.40109	3296.8	3697.9	8.0289	0.33393	3295.6	3696.3	7.9434	0.28596	3294.4	3694.8	7.8710
700	0.44779	3475.4	3923.1	8.2731	0.37294	3474.5	3922.0	8.1881	0.31947	3473.6	3920.9	8.1160
800	0.49432	3660.5	4154.8	8.4996	0.41177	3659.8	4153.9	8.4149	0.35281	3659.1	4153.0	8.3431
900	0.54075	3852.2	4392.9	8.7118	0.45051	3851.6	4392.2	8.6272	0.38606	3851.0	4391.5	8.5555
1000	0.58712	4050.5	4637.6	8.9119	0.48919	4050.0	4637.0	8.8274	0.41924	4049.5	4636.4	8.7558
1100	0.63345	4255.1	4888.5	9.1016	0.52783	4254.6	4888.0	9.0171	0.45239	4254.1	4887.5	8.9456
1200	0.67977	4465.6	5145.4	9.2821	0.56646	4465.1	5144.9	9.1977	0.48552	4464.6	5144.4	9.1262
1300	0.72608	4681.3	5407.4	9.4542	0.60507	4680.9	5406.9	9.3698	0.51864	4680.4	5406.5	9.2983
	P = 1.60 MPa (201.40)				P = 1.80 MPa (207.15)				P = 2.00 MPa (212.42)			
Sat.	0.12380	2595.9	2794.0	6.4217	0.11042	2598.4	2797.1	6.3793	0.09963	2600.3	2799.5	6.3408
225	0.13287	2644.6	2857.2	6.5518	0.11673	2636.6	2846.7	6.4807	0.10377	2628.3	2835.8	6.4146
250	0.14184	2692.3	2919.2	6.6732	0.12497	2686.0	2911.0	6.6066	0.11144	2679.6	2902.5	6.5452
300	0.15862	2781.0	3034.8	6.8844	0.14021	2776.8	3029.2	6.8226	0.12547	2772.6	3023.5	6.7663
350	0.17456	2866.0	3145.4	7.0693	0.15457	2862.9	3141.2	7.0099	0.13857	2859.8	3137.0	6.9562
400	0.19005	2950.1	3254.2	7.2373	0.16847	2947.7	3250.9	7.1793	0.15120	2945.2	3247.6	7.1270
500	0.22029	3119.5	3471.9	7.5389	0.19550	3117.8	3469.7	7.4824	0.17568	3116.2	3467.6	7.4316
600	0.24998	3293.3	3693.2	7.8080	0.22199	3292.1	3691.7	7.7523	0.19960	3290.9	3690.1	7.7023
700	0.27937	3472.7	3919.7	8.0535	0.24818	3471.9	3918.6	7.9983	0.22323	3471.0	3917.5	7.9487
800	0.30859	3658.4	4152.1	8.2808	0.27420	3657.7	4151.3	8.2258	0.24668	3657.0	4150.4	8.1766
900	0.33772	3850.5	4390.8	8.4934	0.30012	3849.9	4390.1	8.4386	0.27004	3849.3	4389.4	8.3895
1000	0.36678	4049.0	4635.8	8.6938	0.32598	4048.4	4635.2	8.6390	0.29333	4047.9	4634.6	8.5900
1100	0.39581	4253.7	4887.0	8.8837	0.35180	4253.2	4886.4	8.8290	0.31659	4252.7	4885.9	8.7800
1200	0.42482	4464.2	5143.9	9.0642	0.37761	4463.7	5143.4	9.0096	0.33984	4463.2	5142.9	8.9606
1300	0.45382	4679.9	5406.0	9.2364	0.40340	4679.4	5405.6	9.1817	0.36306	4679.0	5405.1	9.1328
	P = 2.50 MPa (223.99)				P = 3.00 MPa (233.90)				P = 3.50 MPa (242.60)			
Sat.	0.07998	2603.1	2803.1	6.2574	0.06668	2604.1	2804.1	6.1869	0.05707	2603.7	2803.4	6.1252
225	0.08027	2605.6	2806.3	6.2638	—	—	—	—	—	—	—	—
250	0.08700	2662.5	2880.1	6.4084	0.07058	2644.0	2855.8	6.2871	0.05873	2623.7	2829.2	6.1748
300	0.09890	2761.6	3008.8	6.6437	0.08114	2750.0	2993.5	6.5389	0.06842	2738.0	2977.5	6.4460
350	0.10976	2851.8	3126.2	6.8402	0.09053	2843.7	3115.3	6.7427	0.07678	2835.3	3104.0	6.6578
400	0.12010	2939.0	3239.3	7.0147	0.09936	2932.7	3230.8	6.9211	0.08453	2926.4	3222.2	6.8404
450	0.13014	3025.4	3350.8	7.1745	0.10787	3020.4	3344.0	7.0833	0.09196	3015.3	3337.2	7.0051
500	0.13998	3112.1	3462.0	7.3233	0.11619	3107.9	3456.5	7.2337	0.09918	3103.7	3450.9	7.1571
600	0.15930	3288.0	3686.2	7.5960	0.13243	3285.0	3682.3	7.5084	0.11324	3282.1	3678.4	7.4338
700	0.17832	3468.8	3914.6	7.8435	0.14838	3466.6	3911.7	7.7571	0.12699	3464.4	3908.8	7.6837

TABLA A.1.3SI (Continuación) *Vapor de agua sobrecalentado (unidades SI)*

	P = 2.50 MPa (223.99)				P = 3.00 MPa (233.90)				P = 3.50 MPa (242.60)			
T	v	u	h	s	v	u	h	s	v	u	h	s
800	0.19716	3655.3	4148.2	8.0720	0.16414	3653.6	4146.0	7.9862	0.14056	3651.8	4143.8	7.9135
900	0.21590	3847.9	4387.6	8.2853	0.17980	3846.5	4385.9	8.1999	0.15402	3845.0	4384.1	8.1275
1000	0.23458	4046.7	4633.1	8.4860	0.19541	4045.4	4631.6	8.4009	0.16743	4044.1	4630.1	8.3288
1100	0.25322	4251.5	4884.6	8.6761	0.21098	4250.3	4883.3	8.5911	0.18080	4249.1	4881.9	8.5191
1200	0.27185	4462.1	5141.7	8.8569	0.22652	4460.9	5140.5	8.7719	0.19415	4459.8	5139.3	8.7000
1300	0.29046	4677.8	5404.0	9.0291	0.24206	4676.6	5402.8	8.9442	0.20749	4675.5	5401.7	8.8723
	P = 4.00 MPa (250.40)				P = 4.50 MPa (257.48)				P = 5.00 MPa (263.99)			
Sat.	0.04978	2602.3	2801.4	6.0700	0.04406	2600.0	2798.3	6.0198	0.03944	2597.1	2794.3	5.9733
275	0.05457	2667.9	2886.2	6.2284	0.04730	2650.3	2863.1	6.1401	0.04141	2631.2	2838.3	6.0543
300	0.05884	2725.3	2960.7	6.3614	0.05135	2712.0	2943.1	6.2827	0.04532	2697.9	2924.5	6.2083
350	0.06645	2826.6	3092.4	6.5820	0.05840	2817.8	3080.6	6.5130	0.05194	2808.7	3068.4	6.4492
400	0.07341	2919.9	3213.5	6.7689	0.06475	2913.3	3204.7	6.7046	0.05781	2906.6	3195.6	6.6458
450	0.08003	3010.1	3330.2	6.9362	0.07074	3004.9	3323.2	6.8745	0.06330	2999.6	3316.1	6.8185
500	0.08643	3099.5	3445.2	7.0900	0.07651	3095.2	3439.5	7.0300	0.06857	3090.9	3433.8	6.9758
600	0.09885	3279.1	3674.4	7.3688	0.08765	3276.0	3670.5	7.3109	0.07869	3273.0	3666.5	7.2588
700	0.11095	3462.1	3905.9	7.6198	0.09847	3459.9	3903.0	7.5631	0.08849	3457.7	3900.1	7.5122
800	0.12287	3650.1	4141.6	7.8502	0.10911	3648.4	4139.4	7.7942	0.09811	3646.6	4137.2	7.7440
900	0.13469	3843.6	4382.3	8.0647	0.11965	3842.1	4380.6	8.0091	0.10762	3840.7	4378.8	7.9593
1000	0.14645	4042.9	4628.7	8.2661	0.13013	4041.6	4627.2	8.2108	0.11707	4040.3	4625.7	8.1612
1100	0.15817	4248.0	4880.6	8.4566	0.14056	4246.8	4879.3	8.4014	0.12648	4245.6	4878.0	8.3519
1200	0.16987	4458.6	5138.1	8.6376	0.15098	4457.4	5136.9	8.5824	0.13587	4456.3	5135.7	8.5330
1300	0.18156	4674.3	5400.5	8.8099	0.16139	4673.1	5399.4	8.7548	0.14526	4672.0	5398.2	8.7055
	P = 6.00 MPa (275.64)				P = 7.00 MPa (285.88)				P = 8.00 MPa (295.06)			
Sat.	0.03244	2589.7	2784.3	5.8891	0.02737	2580.5	2772.1	5.8132	0.02352	2569.8	2757.9	5.7431
300	0.03616	2667.2	2884.2	6.0673	0.02947	2632.1	2838.4	5.9304	0.02426	2590.9	2785.0	5.7905
350	0.04223	2789.6	3043.0	6.3334	0.03524	2769.3	3016.0	6.2282	0.02995	2747.7	2987.3	6.1300
400	0.04739	2892.8	3177.2	6.5407	0.03993	2878.6	3158.1	6.4477	0.03432	2863.8	3138.3	6.3633
450	0.05214	2988.9	3301.8	6.7192	0.04416	2977.9	3287.0	6.6326	0.03817	2966.7	3272.0	6.5550
500	0.05665	3082.2	3422.1	6.8802	0.04814	3073.3	3410.3	6.7974	0.04175	3064.3	3398.3	6.7239

	P = 6.00 MPa (275.64)				P = 7.00 MPa (285.88)				P = 8.00 MPa (295.06)			
T	v	u	h	s	v	u	h	s	v	u	h	s
550	0.06101	3174.6	3540.6	7.0287	0.05195	3167.2	3530.9	6.9486	0.04516	3159.8	3521.0	6.8778
600	0.06525	3266.9	3658.4	7.1676	0.05565	3260.7	3650.3	7.0894	0.04845	3254.4	3642.0	7.0205
700	0.07352	3453.2	3894.3	7.4234	0.06283	3448.6	3888.4	7.3476	0.05481	3444.0	3882.5	7.2812
800	0.08160	3643.1	4132.7	7.6566	0.06981	3639.6	4128.3	7.5822	0.06097	3636.1	4123.8	7.5173
900	0.08958	3837.8	4375.3	7.8727	0.07669	3835.0	4371.8	7.7991	0.06702	3832.1	4368.3	7.7350
1000	0.09749	4037.8	4622.7	8.0751	0.08350	4035.3	4619.8	8.0020	0.07301	4032.8	4616.9	7.9384
1100	0.10536	4243.3	4875.4	8.2661	0.09027	4240.9	4872.8	8.1933	0.07896	4238.6	4870.3	8.1299
1200	0.11321	4454.0	5133.3	8.4473	0.09703	4451.7	5130.9	8.3747	0.08489	4449.4	5128.5	8.3115
1300	0.12106	4669.6	5396.0	8.6199	0.10377	4667.3	5393.7	8.5472	0.09080	4665.0	5391.5	8.4842
	P = 9.00 MPa (303.40)				P = 10.00 MPa (311.06)				P = 12.50 MPa (327.89)			
Sat.	0.02048	2557.8	2742.1	5.6771	0.01803	2544.4	2724.7	5.6140	0.01350	2505.1	2673.8	5.4623
325	0.02327	2646.5	2855.9	5.8711	0.01986	2610.4	2809.0	5.7568	—	—	—	—
350	0.02580	2724.4	2956.5	6.0361	0.02242	2699.2	2923.4	5.9442	0.01613	2624.6	2826.2	5.7117
400	0.02993	2848.4	3117.8	6.2853	0.02641	2832.4	3096.5	6.2119	0.02000	2789.3	3039.3	6.0416
450	0.03350	2955.1	3256.6	6.4843	0.02975	2943.3	3240.8	6.4189	0.02299	2912.4	3199.8	6.2718
500	0.03677	3055.1	3386.1	6.6575	0.03279	3045.8	3373.6	6.5965	0.02560	3021.7	3341.7	6.4617
550	0.03987	3152.2	3511.0	6.8141	0.03564	3144.5	3500.9	6.7561	0.02801	3124.9	3475.1	6.6289
600	0.04285	3248.1	3633.7	6.9588	0.03837	3241.7	3625.3	6.9028	0.03029	3225.4	3604.0	6.7810
650	0.04574	3343.7	3755.3	7.0943	0.04101	3338.2	3748.3	7.0397	0.03248	3324.4	3730.4	6.9218
700	0.04857	3439.4	3876.5	7.2221	0.04358	3434.7	3870.5	7.1687	0.03460	3422.9	3855.4	7.0536
800	0.05409	3632.5	4119.4	7.4597	0.04859	3629.0	4114.9	7.4077	0.03869	3620.0	4103.7	7.2965
900	0.05950	3829.2	4364.7	7.6782	0.05349	3826.3	4361.2	7.6272	0.04267	3819.1	4352.5	7.5181
1000	0.06485	4030.3	4613.9	7.8821	0.05832	4027.8	4611.0	7.8315	0.04658	4021.6	4603.8	7.7237
1100	0.07016	4236.3	4867.7	8.0739	0.06312	4234.0	4865.1	8.0236	0.05045	4228.2	4858.8	7.9165
1200	0.07544	4447.2	5126.2	8.2556	0.06789	4444.9	5123.8	8.2054	0.05430	4439.3	5118.0	8.0987
1300	0.08072	4662.7	5389.2	8.4283	0.07265	4660.4	5387.0	8.3783	0.05813	4654.8	5381.4	8.2717
	P = 15 MPa (342.24)				P = 17.5 MPa (354.75)				P = 20 MPa (365.81)			
Sat.	.010338	2455.4	2610.5	5.3097	.0079204	2390.2	2528.8	5.1418	.0058342	2293.1	2409.7	4.9269
350	.011470	2520.4	2692.4	5.4420	—	—	—	—	—	—	—	—
400	.015649	2740.7	2975.4	5.8810	.0124477	2685.0	2902.8	5.7212	.0099423	2619.2	2818.1	5.5539
450	.018446	2879.5	3156.2	6.1403	.0151740	2844.2	3109.7	6.0182	.0126953	2806.2	3060.1	5.9016
500	.020800	2996.5	3308.5	6.3442	.0173585	2970.3	3274.0	6.2382	.0147683	2942.8	3238.2	6.1400
550	.022927	3104.7	3448.6	6.5198	.0192877	3083.8	3421.4	6.4229	.0165553	3062.3	3393.5	6.3347
600	.024911	3208.6	3582.3	6.6775	.0210640	3191.5	3560.1	6.5866	.0181781	3174.0	3537.6	6.5048
650	.026797	3310.4	3712.3	6.8223	.0227372	3296.0	3693.9	6.7356	.0196929	3281.5	3675.3	6.6582

TABLA A.1.3SI (Continuación) *Vapor de agua sobrecalentado (unidades SI)*

	P = 15 MPa (342.24)				P = 17.5 MPa (354.75)				P = 20 MPa (365.81)			
T	v	u	h	s	v	u	h	s	v	u	h	s
700	.028612	3410.9	3840.1	6.9572	.0243365	3398.8	3824.7	6.8736	.0211311	3386.5	3809.1	6.7993
800	.032096	3611.0	4092.4	7.2040	.0273849	3601.9	4081.1	7.1245	.0238532	3592.7	4069.8	7.0544
900	.035457	3811.9	4343.8	7.4279	.0303071	3804.7	4335.1	7.3507	.0264463	3797.4	4326.4	7.2830
1000	.038748	4015.4	4596.6	7.6347	.0331580	4009.3	4589.5	7.5588	.0289666	4003.1	4582.5	7.4925
1100	.042001	4222.6	4852.6	7.8282	.0359695	4216.9	4846.4	7.7530	.0314471	4211.3	4840.2	7.6874
1200	.045233	4433.8	5112.3	8.0108	.0387605	4428.3	5106.6	7.9359	.0339071	4422.8	5101.0	7.8706
1300	.048455	4649.1	5375.9	8.1839	.0415417	4643.5	5370.5	8.1093	.0363574	4638.0	5365.1	8.0441
	P = 25 MPa				P = 30 MPa				P = 35 MPa			
375	.001973	1798.6	1847.9	4.0319	.001789	1737.8	1791.4	3.9303	.001700	1702.9	1762.4	3.8721
400	.006004	2430.1	2580.2	5.1418	.002790	2067.3	2151.0	4.4728	.002100	1914.0	1987.5	4.2124
425	.007882	2609.2	2806.3	5.4722	.005304	2455.1	2614.2	5.1503	.003428	2253.4	2373.4	4.7747
450	.009162	2720.7	2949.7	5.6743	.006735	2619.3	2821.4	5.4423	.004962	2498.7	2672.4	5.1962
500	.011124	2884.3	3162.4	5.9592	.008679	2820.7	3081.0	5.7904	.006927	2751.9	2994.3	5.6281
550	.012724	3017.5	3335.6	6.1764	.010168	2970.3	3275.4	6.0342	.008345	2920.9	3213.0	5.9025
600	.014138	3137.9	3491.4	6.3602	.011446	3100.5	3443.9	6.2330	.009527	3062.0	3395.5	6.1178
650	.015433	3251.6	3637.5	6.5229	.012596	3221.0	3598.9	6.4057	.010575	3189.8	3559.9	6.3010
700	.016647	3361.4	3777.6	6.6707	.013661	3335.8	3745.7	6.5606	.011533	3309.9	3713.5	6.4631
800	.018913	3574.3	4047.1	6.9345	.015623	3555.6	4024.3	6.8332	.013278	3536.8	4001.5	6.7450
900	.021045	3783.0	4309.1	7.1679	.017448	3768.5	4291.9	7.0717	.014883	3754.0	4274.9	6.9886
1000	.023102	3990.9	4568.5	7.3801	.019196	3978.8	4554.7	7.2867	.016410	3966.7	4541.1	7.2063
1100	.025119	4200.2	4828.2	7.5765	.020903	4189.2	4816.3	7.4845	.017895	4178.3	4804.6	7.4056
1200	.027115	4412.0	5089.9	7.7604	.022589	4401.3	5079.0	7.6691	.019360	4390.7	5068.4	7.5910
1300	.029101	4626.9	5354.4	7.9342	.024266	4616.0	5344.0	7.8432	.020815	4605.1	5333.6	7.7652
	P = 40 MPa				P = 50 MPa				P = 60 MPa			
375	.0016406	1677.1	1742.7	3.8289	.0015593	1638.6	1716.5	3.7638	.0015027	1609.3	1699.5	3.7140
400	.0019077	1854.5	1930.8	4.1134	.0017309	1788.0	1874.6	4.0030	.0016335	1745.3	1843.4	3.9317
425	.0025319	2096.8	2198.1	4.5028	.0020071	1959.6	2060.0	4.2733	.0018165	1892.7	2001.7	4.1625
450	.0036931	2365.1	2512.8	4.9459	.0024862	2159.6	2283.9	4.5883	.0020850	2053.9	2179.0	4.4119
500	.0056225	2678.4	2903.3	5.4699	.0038924	2525.5	2720.1	5.1725	.0029557	2390.5	2567.9	4.9320

TABLA A.1.4SI *Agua líquida comprimida (unidades SI)*

	P = 5.00 MPa (263.99)				P = 10.00 MPa (311.06)				P = 15.00 MPa (342.24)			
T	v	u	h	s	v	u	h	s	v	u	h	s
600	.0080943	3022.6	3346.4	6.0113	.0061123	2942.0	3247.6	5.8177	.0048345	2861.1	3151.2	5.6451
650	.0090636	3158.0	3520.6	6.2054	.0069657	3093.6	3441.8	6.0342	.0055953	3028.8	3364.6	5.8829
700	.0099415	3283.6	3681.3	6.3750	.0077274	3230.5	3616.9	6.2189	.0062719	3177.3	3553.6	6.0824
800	.0115228	3517.9	3978.8	6.6662	.0090761	3479.8	3933.6	6.5290	.0074588	3441.6	3889.1	6.4110
900	.0129626	3739.4	4257.9	6.9150	.0102831	3710.3	4224.4	6.7882	.0085083	3681.0	4191.5	6.6805
1000	.0143238	3954.6	4527.6	7.1356	.0114113	3930.5	4501.1	7.0146	.0094800	3906.4	4475.2	6.9126
1100	.0156426	4167.4	4793.1	7.3364	.0124966	4145.7	4770.6	7.2183	.0104091	4124.1	4748.6	7.1194
1200	.0169403	4380.1	5057.7	7.5224	.0135606	4359.1	5037.2	7.4058	.0113167	4338.2	5017.2	7.3082
1300	.0182292	4594.3	5323.5	7.6969	.0146159	4572.8	5303.6	7.5807	.0122155	4551.4	5284.3	7.4837

Compressed Liquid Water (SI Units)

	P = 5.00 MPa (263.99)				P = 10.00 MPa (311.06)				P = 15.00 MPa (342.24)			
T	v	u	h	s	v	u	h	s	v	u	h	s
Sat.	.0012859	1147.78	1154.21	2.9201	.0014524	1393.00	1407.53	3.3595	.0016581	1585.58	1610.45	3.6847
0	.0009977	0.03	5.02	0.0001	.0009952	0.10	10.05	0.0003	.0009928	0.15	15.04	0.0004
20	.0009995	83.64	88.64	0.2955	.0009972	83.35	93.32	0.2945	.0009950	83.05	97.97	0.2934
40	.0010056	166.93	171.95	0.5705	.0010034	166.33	176.36	0.5685	.0010013	165.73	180.75	0.5665
60	.0010149	250.21	255.28	0.8284	.0010127	249.34	259.47	0.8258	.0010105	248.49	263.65	0.8231
80	.0010268	333.69	338.83	1.0719	.0010245	332.56	342.81	1.0687	.0010222	331.46	346.79	1.0655
100	.0010410	417.50	422.71	1.3030	.0010385	416.09	426.48	1.2992	.0010361	414.72	430.26	1.2954
120	.0010576	501.79	507.07	1.5232	.0010549	500.07	510.61	1.5188	.0010522	498.39	514.17	1.5144
140	.0010768	586.74	592.13	1.7342	.0010737	584.67	595.40	1.7291	.0010707	582.64	598.70	1.7241
160	.0010988	672.61	678.10	1.9374	.0010953	670.11	681.07	1.9316	.0010918	667.69	684.07	1.9259
180	.0011240	759.62	765.24	2.1341	.0011199	756.63	767.83	2.1274	.0011159	753.74	770.48	2.1209
200	.0011530	848.08	853.85	2.3254	.0011480	844.49	855.97	2.3178	.0011433	841.04	858.18	2.3103
220	.0011866	938.43	944.36	2.5128	.0011805	934.07	945.88	2.5038	.0011748	929.89	947.52	2.4952
240	.0012264	1031.34	1037.47	2.6978	.0012187	1025.94	1038.13	2.6872	.0012114	1020.82	1038.99	2.6770

TABLA A.1.4SI (Continuación) *Agua líquida comprimida (unidades SI)*

	P = 5.00 MPa (263.99)				P = 10.00 MPa (311.06)				P = 15.00 MPa (342.24)			
T	v	u	h	s	v	u	h	s	v	u	h	s
260	.0012748	1127.92	1134.30	2.8829	.0012645	1121.03	1133.68	2.8698	.0012550	1114.59	1133.41	2.8575
280					.0013216	1220.90	1234.11	3.0547	.0013084	1212.47	1232.09	3.0392
300					.0013972	1328.34	1342.31	3.2468	.0013770	1316.58	1337.23	3.2259
320									.0014724	1431.05	1453.13	3.4246
340									.0016311	1567.42	1591.88	3.6545
	P = 20 MPa (365.81)				P = 30 MPa				P = 50 MPa			
Sat.	.0020353	1785.47	1826.18	4.0137	—	—	—	—	—	—	—	—
0	.0009904	0.20	20.00	0.0004	.0009856	0.25	29.82	0.0001	.0009766	0.20	49.03	-0.0014
20	.0009928	82.75	102.61	0.2922	.0009886	82.16	111.82	0.2898	.0009804	80.98	130.00	0.2847
40	.0009992	165.15	185.14	0.5646	.0009951	164.01	193.87	0.5606	.0009872	161.84	211.20	0.5526
60	.0010084	247.66	267.82	0.8205	.0010042	246.03	276.16	0.8153	.0009962	242.96	292.77	0.8051
80	.0010199	330.38	350.78	1.0623	.0010156	328.28	358.75	1.0561	.0010073	324.32	374.68	1.0439
100	.0010337	413.37	434.04	1.2917	.0010290	410.76	441.63	1.2844	.0010201	405.86	456.87	1.2703
120	.0010496	496.75	517.74	1.5101	.0010445	493.58	524.91	1.5017	.0010348	487.63	539.37	1.4857
140	.0010678	580.67	602.03	1.7192	.0010621	576.86	608.73	1.7097	.0010515	569.76	622.33	1.6915
160	.0010885	665.34	687.11	1.9203	.0010821	660.81	693.27	1.9095	.0010703	652.39	705.91	1.8890
180	.0011120	750.94	773.18	2.1146	.0011047	745.57	778.71	2.1024	.0010912	735.68	790.24	2.0793
200	.0011387	837.70	860.47	2.3031	.0011302	831.34	865.24	2.2892	.0011146	819.73	875.46	2.2634
220	.0011693	925.89	949.27	2.4869	.0011590	918.32	953.09	2.4710	.0011408	904.67	961.71	2.4419
240	.0012046	1015.94	1040.04	2.6673	.0011920	1006.84	1042.60	2.6489	.0011702	990.69	1049.20	2.6158
260	.0012462	1108.53	1133.45	2.8459	.0012303	1097.38	1134.29	2.8242	.0012034	1078.06	1138.23	2.7860
280	.0012965	1204.69	1230.62	3.0248	.0012755	1190.69	1228.96	2.9985	.0012415	1167.19	1229.26	2.9536
300	.0013596	1306.10	1333.29	3.2071	.0013304	1287.89	1327.80	3.1740	.0012860	1258.66	1322.95	3.1200
320	.0014437	1415.66	1444.53	3.3978	.0013997	1390.64	1432.63	3.3538	.0013388	1353.23	1420.17	3.2867
340	.0015683	1539.64	1571.01	3.6074	.0014919	1501.71	1546.47	3.5425	.0014032	1451.91	1522.07	3.4556
360	.0018226	1702.78	1739.23	3.8770	.0016265	1626.57	1675.36	3.7492	.0014838	1555.97	1630.16	3.6290
380	—	—	—	—	.0018691	1781.35	1837.43	4.0010	.0015883	1667.13	1746.54	3.8100

TABLA A.1.5SI *Agua sólido saturado-vapor saturado (unidades SI)*

	Volumen específico, m^3/kg			Energía interna, kJ/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
Temp. °C T	Presión kPa, P	Sólido saturado $v_i \times 10^{-3}$	Vapor saturado v_g	Sólido saturado u_i	Evap. u_{ig}	Vapor saturado u_g	Sólido saturado h_i	Evap. h_{ig}	Vapor saturado h_g	Vapor saturado s_i	Evap. s_{ig}	Vapor saturado s_g
0.01	0.6113	1.0908	206.153	−333.40	2708.7	2375.3	−333.40	2834.7	2501.3	−1.2210	10.3772	9.1562
0	0.6108	1.0908	206.315	−333.42	2708.7	2375.3	−333.42	2834.8	2501.3	−1.2211	10.3776	9.1565
−2	0.5177	1.0905	241.663	−337.61	2710.2	2372.5	−337.61	2835.3	2497.6	−1.2369	10.4562	9.2193
−4	0.4376	1.0901	283.799	−341.78	2711.5	2369.8	−341.78	2835.7	2494.0	−1.2526	10.5358	9.2832
−6	0.3689	1.0898	334.139	−345.91	2712.9	2367.0	−345.91	2836.2	2490.3	−1.2683	10.6165	9.3482
−8	0.3102	1.0894	394.414	−350.02	2714.2	2364.2	−350.02	2836.6	2486.6	−1.2839	10.6982	9.4143
−10	0.2601	1.0891	466.757	−354.09	2715.5	2361.4	−354.09	2837.0	2482.9	−1.2995	10.7809	9.4815
−12	0.2176	1.0888	553.803	−358.14	2716.8	2358.7	−358.14	2837.3	2479.2	−1.3150	10.8648	9.5498
−14	0.1815	1.0884	658.824	−362.16	2718.0	2355.9	−362.16	2837.6	2475.5	−1.3306	10.9498	9.6192
−16	0.1510	1.0881	785.907	−366.14	2719.2	2353.1	−366.14	2837.9	2471.8	−1.3461	11.0359	9.6898
−18	0.1252	1.0878	940.183	−370.10	2720.4	2350.3	−370.10	2838.2	2468.1	−1.3617	11.1233	9.7616
−20	0.10355	1.0874	1128.113	−374.03	2721.6	2347.5	−374.03	2838.4	2464.3	−1.3772	11.2120	9.8348
−22	0.08535	1.0871	1357.864	−377.93	2722.7	2344.7	−377.93	2838.6	2460.6	−1.3928	11.3020	9.9093
−24	0.07012	1.0868	1639.753	−381.80	2723.7	2342.0	−381.80	2838.7	2456.9	−1.4083	11.3935	9.9852
−26	0.05741	1.0864	1986.776	−385.64	2724.8	2339.2	−385.64	2838.9	2453.2	−1.4239	11.4864	10.0625
−28	0.04684	1.0861	2415.201	−389.45	2725.8	2336.4	−389.45	2839.0	2449.5	−1.4394	11.5808	10.1413
−30	0.03810	1.0858	2945.228	−393.23	2726.8	2333.6	−393.23	2839.0	2445.8	−1.4550	11.6765	10.2215
−32	0.03090	1.0854	3601.823	−396.98	2727.8	2330.8	−396.98	2839.1	2442.1	−1.4705	11.7733	10.3028
−34	0.02499	1.0851	4416.253	−400.71	2728.7	2328.0	−400.71	2839.1	2438.4	−1.4860	11.8713	10.3853
−36	0.02016	1.0848	5430.116	−404.40	2729.6	2325.2	−404.40	2839.1	2434.7	−1.5014	11.9704	10.4690
−38	0.01618	1.0844	6707.022	−408.06	2730.5	2322.4	−408.06	2839.0	2431.0	−1.5168	12.0714	10.5546
−40	0.01286	1.0841	8366.396	−411.70	2731.3	2319.6	−411.70	2838.9	2427.2	−1.5321	12.1768	10.6447

TABLA A.2SI *Propiedades termodinámicas del amoniaco*
TABLA A.2.1SI *Amoniaco saturado (unidades SI)*

Temp. °C	Presión abs. kPa, P	Volumen específico, m^3/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
		Líquido saturado v_f	Evap. v_{fg}	Vapor saturado v_g	Líquido saturado h_f	Evap. h_{fg}	Vapor saturado h_g	Líquido saturado s_f	Evap. s_{fg}	Vapor saturado s_g
−50	40.86	0.001424	2.62524	2.62667	−43.76	1416.34	1372.57	−0.1916	6.3470	6.1553
−48	45.94	0.001429	2.35297	2.35440	−35.04	1410.95	1375.90	−0.1528	6.2666	6.1139
−46	51.52	0.001434	2.11359	2.11503	−26.31	1405.50	1379.19	−0.1142	6.1875	6.0733
−44	57.66	0.001439	1.90262	1.90406	−17.56	1400.00	1382.44	−0.0759	6.1095	6.0336
−42	64.38	0.001444	1.71625	1.71769	−8.79	1394.44	1385.65	−0.0378	6.0326	5.9948
−40	71.72	0.001450	1.55124	1.55269	0	1388.82	1388.82	0	5.9568	5.9568
−38	79.74	0.001455	1.40482	1.40627	8.81	1383.13	1391.94	0.0376	5.8820	5.9196
−36	88.48	0.001460	1.27461	1.27607	17.64	1377.39	1395.03	0.0749	5.8082	5.8831
−34	97.98	0.001465	1.15857	1.16004	26.49	1371.58	1398.07	0.1120	5.7353	5.8473
−32	108.29	0.001471	1.05496	1.05643	35.36	1365.70	1401.06	0.1489	5.6634	5.8123
−30	119.46	0.001476	0.96226	0.96374	44.26	1359.76	1404.01	0.1856	5.5924	5.7780
−28	131.54	0.001482	0.87916	0.88064	53.17	1353.74	1406.92	0.2220	5.5223	5.7443
−26	144.59	0.001487	0.80453	0.80602	62.11	1347.66	1409.77	0.2582	5.4530	5.7113
−24	158.65	0.001493	0.73738	0.73887	71.07	1341.51	1412.58	0.2942	5.3846	5.6788
−22	173.80	0.001498	0.67685	0.67835	80.05	1335.29	1415.34	0.3301	5.3170	5.6470
−20	190.08	0.001504	0.62220	0.62371	89.05	1329.00	1418.05	0.3657	5.2501	5.6158
−18	207.56	0.001510	0.57277	0.57428	98.08	1322.64	1420.71	0.4011	5.1840	5.5851
−16	226.29	0.001516	0.52800	0.52951	107.12	1316.20	1423.32	0.4363	5.1187	5.5550
−14	246.35	0.001522	0.48737	0.48889	116.19	1309.68	1425.88	0.4713	5.0541	5.5254
−12	267.79	0.001528	0.45045	0.45197	125.29	1303.09	1428.38	0.5061	4.9901	5.4963
−10	290.67	0.001534	0.41684	0.41837	134.41	1296.42	1430.83	0.5408	4.9269	5.4676
−8	315.08	0.001540	0.38621	0.38775	143.55	1289.67	1433.22	0.5753	4.8642	5.4395
−6	341.07	0.001546	0.35824	0.35979	152.72	1282.84	1435.56	0.6095	4.8023	5.4118
−4	368.72	0.001553	0.33268	0.33423	161.91	1275.93	1437.84	0.6437	4.7409	5.3846
−2	398.10	0.001559	0.30928	0.31084	171.12	1268.94	1440.06	0.6776	4.6801	5.3577

Temp. °C	Presión abs. kPa, P	Volumen específico, m^3/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
		Líquido saturado v_f	Evap. v_{fg}	Vapor saturado v_g	Líquido saturado h_f	Evap. h_{fg}	Vapor saturado h_g	Líquido saturado s_f	Evap. s_{fg}	Vapor saturado s_g
0	429.29	0.001566	0.28783	0.28940	180.36	1261.86	1442.22	0.7114	4.6199	5.3313
2	462.34	0.001573	0.26815	0.26972	189.63	1254.69	1444.32	0.7450	4.5603	5.3053
4	497.35	0.001579	0.25005	0.25163	198.93	1247.43	1446.35	0.7785	4.5012	5.2796
6	534.39	0.001586	0.23341	0.23499	208.25	1240.08	1448.32	0.8118	4.4426	5.2543
8	573.54	0.001593	0.21807	0.21966	217.60	1232.63	1450.23	0.8449	4.3845	5.2294
10	614.87	0.001600	0.20392	0.20553	226.97	1225.10	1452.07	0.8779	4.3269	5.2048
12	658.48	0.001608	0.19086	0.19247	236.38	1217.46	1453.84	0.9108	4.2698	5.1805
14	704.43	0.001615	0.17878	0.18040	245.81	1209.72	1455.53	0.9435	4.2131	5.1565
16	752.81	0.001623	0.16761	0.16923	255.28	1201.88	1457.16	0.9760	4.1568	5.1328
18	803.71	0.001630	0.15725	0.15888	264.77	1193.94	1458.71	1.0085	4.1009	5.1094
20	857.22	0.001638	0.14764	0.14928	274.30	1185.89	1460.18	1.0408	4.0455	5.0863
22	913.41	0.001646	0.13872	0.14037	283.85	1177.73	1461.58	1.0730	3.9904	5.0634
24	972.38	0.001654	0.13043	0.13208	293.44	1169.45	1462.89	1.1050	3.9357	5.0407
26	1034.21	0.001663	0.12272	0.12438	303.07	1161.06	1464.13	1.1370	3.8813	5.0182
28	1099.00	0.001671	0.11553	0.11720	312.72	1152.55	1465.27	1.1688	3.8272	4.9960
30	1166.83	0.001680	0.10883	0.11051	322.42	1143.92	1466.33	1.2005	3.7735	4.9740
32	1237.80	0.001688	0.10258	0.10427	332.14	1135.16	1467.30	1.2321	3.7200	4.9521
34	1312.00	0.001697	0.09675	0.09845	341.91	1126.27	1468.17	1.2635	3.6669	4.9304
36	1389.52	0.001707	0.09129	0.09300	351.71	1117.25	1468.95	1.2949	3.6140	4.9089
38	1470.46	0.001716	0.08619	0.08790	361.55	1108.09	1469.64	1.3262	3.5613	4.8875
40	1554.92	0.001725	0.08141	0.08313	371.43	1098.79	1470.22	1.3574	3.5088	4.8662
42	1642.98	0.001735	0.07693	0.07866	381.35	1089.34	1470.69	1.3885	3.4566	4.8451
44	1734.75	0.001745	0.07272	0.07447	391.31	1079.75	1471.06	1.4195	3.4045	4.8240
46	1830.33	0.001755	0.06878	0.07053	401.32	1070.00	1471.32	1.4504	3.3526	4.8030
48	1929.82	0.001766	0.06507	0.06684	411.38	1060.09	1471.46	1.4813	3.3009	4.7822
50	2033.32	0.001777	0.06159	0.06336	421.48	1050.01	1471.49	1.5121	3.2493	4.7613

TABLA A.2.2SI *Amoniaco sobrecalentado (unidades SI)*

Presión abs. kPa, (*T saturación*)		Temperatura, °C											
		−20	−10	0	10	20	30	40	50	60	70	80	100
	v	2.4463	2.5471	2.6474	2.7472	2.8466	2.9458	3.0447	3.1435	3.2421	3.3406	3.4390	—
50	*h*	1434.6	1455.7	1476.9	1498.1	1519.3	1540.6	1562.0	1583.5	1605.1	1626.9	1648.8	—
(−46.53)	*s*	6.3187	6.4006	6.4795	6.5556	6.6293	6.7008	6.7703	6.8379	6.9038	6.9682	7.0312	—
	v	1.6222	1.6905	1.7582	1.8255	1.8924	1.9591	2.0255	2.0917	2.1577	2.2237	2.2895	—
75	*h*	1431.7	1453.3	1474.8	1496.2	1517.7	1539.2	1560.7	1582.4	1604.1	1626.0	1648.0	—
(−39.16)	*s*	6.1120	6.1954	6.2756	6.3527	6.4272	6.4993	6.5693	6.6373	6.7036	6.7683	6.8315	—
	v	1.2101	1.2621	1.3136	1.3647	1.4153	1.4657	1.5158	1.5658	1.6156	1.6652	1.7148	1.8137
100	*h*	1428.8	1450.8	1472.6	1494.4	1516.1	1537.7	1559.5	1581.2	1603.1	1625.1	1647.1	1691.7
(−33.59)	s	5.9626	6.0477	6.1291	6.2073	6.2826	6.3553	6.4258	6.4943	6.5609	6.6258	6.6892	6.8120
	v	0.9627	1.0051	1.0468	1.0881	1.1290	1.1696	1.2100	1.2502	1.2903	1.3302	1.3700	1.4494
125	*h*	1425.9	1448.3	1470.5	1492.5	1514.4	1536.3	1558.2	1580.1	1602.1	1624.1	1646.3	1691.0
(−29.06)	*s*	5.8446	5.9314	6.0141	6.0933	6.1694	6.2428	6.3138	6.3827	6.4496	6.5149	6.5785	6.7017
	v	0.7977	0.8336	0.8689	0.9037	0.9381	0.9723	1.0062	1.0398	1.0734	1.1068	1.1401	1.2065
150	*h*	1422.9	1445.7	1468.3	1490.6	1512.8	1534.8	1556.9	1578.9	1601.0	1623.2	1645.4	1690.2
(−25.21)	*s*	5.7465	5.8349	5.9189	5.9992	6.0761	6.1502	6.2217	6.2910	6.3583	6.4238	6.4877	6.6112
	v	—	0.6193	0.6465	0.6732	0.6995	0.7255	0.7513	0.7769	0.8023	0.8275	0.8527	0.9028
200	*h*	—	1440.6	1463.8	1486.8	1509.4	1531.9	1554.3	1576.6	1598.9	1621.3	1643.7	1688.8
(−18.85)	*s*	—	5.6791	5.7659	5.8484	5.9270	6.0025	6.0751	6.1453	6.2133	6.2794	6.3437	6.4679
	v	—	0.4905	0.5129	0.5348	0.5563	0.5774	0.5983	0.6190	0.6396	0.6600	0.6803	0.7206
250	*h*	—	1435.3	1459.3	1482.9	1506.0	1529.0	1551.7	1574.3	1596.8	1619.4	1641.9	1687.3
(−13.65)	*s*	—	5.5544	5.6441	5.7288	5.8093	5.8861	5.9599	6.0309	6.0997	6.1663	6.2312	6.3561
	v	—	—	0.4238	0.4425	0.4608	0.4787	0.4964	0.5138	0.5311	0.5483	0.5653	0.5992
300	*h*	—	—	1454.7	1478.9	1502.6	1525.9	1549.0	1571.9	1594.7	1617.5	1640.2	1685.8
(−9.22)	*s*	—	—	5.5420	5.6290	5.7113	5.7896	5.8645	5.9365	6.0060	6.0732	6.1385	6.2642

Presión abs. kPa, (*T saturación*)		Temperatura, °C											
		−20	−10	0	10	20	30	40	50	60	70	80	100
	v	—	—	0.3601	0.3765	0.3925	0.4081	0.4235	0.4386	0.4536	0.4685	0.4832	0.5124
350	*h*	—	—	1449.9	1474.9	1499.1	1522.9	1546.3	1569.5	1592.6	1615.5	1638.4	1684.3
(−5.34)	*s*	—	—	5 4532	5.5427	5.6270	5.7068	5.7828	5.8557	5.9259	5.9938	6.0596	6.1860
	v	—	—	0.3123	0.3270	0.3413	0.3552	0.3688	0.3823	0.3955	0.4086	0.4216	0.4473
400	*h*	—	—	1445.1	1470.7	1495.6	1519.8	1543.6	1567.1	1590.4	1613.6	1636.7	1682.8
(−1.87)	*s*	—	—	5.3741	5.4663	5.5525	5.6338	5.7111	5.7850	5.8560	5.9244	5.9907	6.1179
	v	—	—	—	0.2885	0.3014	0.3140	0.3263	0.3384	0.3503	0.3620	0.3737	0.3967
450	*h*	—	—	—	1466.5	1492.0	1516.7	1540.9	1564.7	1588.2	1611.6	1634.9	1681.3
(1.27)	*s*	—	—	—	5.3972	5.4855	5.5685	5.6470	5.7219	5.7936	5.8627	5.9295	6.0575
		20	**30**	**40**	**50**	**60**	**70**	**80**	**100**	**120**	**140**	**160**	**180**
	v	0.2695	0.2810	0.2923	0.3033	0.3141	0.3248	0.3353	0.3562	0.3768	0.3972	—	—
500	*h*	1488.3	1513.5	1538.1	1562.3	1586.1	1609.6	1633.1	1679.8	1726.6	1773.8	—	—
(4.15)	*s*	5.4244	5.5090	5.5889	5.6647	5.7373	5.8070	5.8744	6.0031	6.1253	6.2422	—	—
	v	0.2215	0.2315	0.2412	0.2506	0.2598	0.2689	0.2778	0.2955	0.3128	0.3300	—	—
600	*h*	1480.8	1507.1	1532.5	1557.3	1581.6	1605.7	1629.5	1676.8	1724.0	1771.5	—	—
(9.29)	*s*	5.3156	5.4037	5.4862	5.5641	5.6383	5.7094	5.7778	5.9081	6.0314	6.1491	—	—
	v	0.1872	0.1961	0.2046	0.2129	0.2210	0.2289	0.2367	0.2521	0.2671	0.2819	—	—
700	*h*	1473.0	1500.4	1526.7	1552.2	1577.1	1601.6	1625.8	1673.7	1721.4	1769.2	—	—
(13.81)	*s*	5.2196	5.3115	5.3968	5.4770	5.5529	5.6254	5.6949	5.8268	5.9512	6.0698	—	—
	v	0.1614	0.1695	0.1772	0.1846	0.1919	0.1990	0.2059	0.2195	0.2328	0.2459	0.2589	—
800	*h*	1464.9	1493.5	1520.8	1547.0	1572.5	1597.5	1622.1	1670.6	1718.7	1766.9	1815.3	—
(17.86)	*s*	5.1328	5.2287	5.3171	5.3996	5.4774	5.5513	5.6219	5.7555	5.8811	6.0006	6.1150	—
	v	—	0.1487	0.1558	0.1626	0.1692	0.1756	0.1819	0.1942	0.2061	0.2179	0.2295	—
900	*h*	—	1486.5	1514.7	1541.7	1567.9	1593.3	1618.4	1667.5	1716.1	1764.5	1813.2	—
(21.53)	*s*	—	5.1530	5.2447	5.3296	5.4093	5.4847	5.5565	5.6919	5.8187	5.9389	6.0541	—
	v	—	0.1321	0.1387	0.1450	0.1511	0.1570	0.1627	0.1739	0.1848	0.1955	0.2060	0.2164
1000	*h*	—	1479.1	1508.5	1536.3	1563.1	1589.1	1614.6	1664.3	1713.4	1762.2	1811.2	1860.5
(24.91)	*s*	—	5.0826	5.1778	5.2654	5.3471	5.4240	5.4971	5.6342	5.7622	5.8834	5.9992	6.1105

TABLA A.2.2SI (Continuación) *Amoniaco sobrecalentado (unidades SI)*

Presión abs. kPa, (*T saturación*)		Temperatura, °C										
		40	**50**	**60**	**70**	**80**	**100**	**120**	**140**	**160**	**180**	**200**	**220**
	v	0.1129	0.1185	0.1238	0.1289	0.1339	0.1435	0.1527	0.1618	0.1707	0.1795	—	—
1200	*h*	1495.4	1525.1	1553.3	1580.5	1606.8	1658.0	1708.0	1757.5	1807.1	1856.9	—	—
(30.95)	*s*	5.0564	5.1497	5.2357	5.3159	5.3916	5.5325	5.6631	5.7860	5.9031	6.0156	—	—
	v	0.0943	0.0994	0.1042	0.1088	0.1132	0.1217	0.1299	0.1378	0.1455	0.1532	—	—
1400	*h*	1481.6	1513.4	1543.1	1571.5	1598.8	1651.4	1702.5	1752.8	1802.9	1853.2	—	—
(36.26)	*s*	4.9463	5.0462	5.1370	5.2209	5.2994	5.4443	5.5775	5.7023	5.8208	5.9343	—	—
	v	—	0.0851	0.0895	0.0937	0.0977	0.1054	0.1127	0.1197	0.1266	0.1334	—	—
1600	*h*	—	1501.0	1532.5	1562.3	1590.7	1644.8	1696.9	1748.0	1798.7	1849.5	—	—
(41.03)	*s*	—	4.9510	5.0472	5.1351	5.2167	5.3659	5.5018	5.6286	5.7485	5.8631	—	—
	v	—	0.0738	0.0780	0.0819	0.0857	0.0927	0.0993	0.1057	0.1119	0.1180	—	—
1800	*h*	—	1487.9	1521.4	1552.7	1582.2	1638.0	1691.2	1743.1	1794.5	1845.7	—	—
(45.37)	s	—	4.8614	4.9637	5.0561	5.1410	5.2948	5.4337	5.5624	5.6838	5.7995	—	—
	v	—	0.0647	0.0687	0.0725	0.0760	0.0825	0.0886	0.0945	0.1002	0.1057	—	—
2000	*h*	—	1473.9	1509.8	1542.7	1573.5	1631.1	1685.5	1738.2	1790.2	1842.0	—	—
(49.36)	*s*	—	4.7754	4.8848	4.9821	5.0707	5.2294	5.3714	5.5022	5.6251	5.7420	—	—

TABLA A.3SI *Propiedades termodinámicas del refrigerante-12 (diclorodifluorometano)*
TABLA A.3.1SI *R-12 saturado (unidades SI)*

Temp. °C	Presión abs. MPa, *P*	Volumen específico, m^3/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
		Líquido saturado v_f	Evap. v_{fg}	Vapor saturado v_g	Líquido saturado h_f	Evap. h_{fg}	Vapor saturado h_g	Líquido saturado s_f	Evap. s_{fg}	Vapor saturado s_g
−90	0.00284	0.000608	4.414937	4.415545	−43.284	189.748	146.464	−0.20863	1.03593	0.82730
−85	0.00424	0.000612	3.036704	3.037316	−39.005	187.737	148.731	−0.18558	0.99771	0.81213
−80	0.00617	0.000617	2.137728	2.138345	−34.721	185.740	151.018	−0.16312	0.96155	0.79843
−75	0.00879	0.000622	1.537030	1.537651	−30.430	183.751	153.321	−0.14119	0.92725	0.78606
−70	0.01227	0.000627	1.126654	1.127280	−26.128	181.764	155.636	−0.11977	0.89465	0.77489
−65	0.01680	0.000632	0.840534	0.841166	−21.814	179.774	157.960	−0.09880	0.86361	0.76480
−60	0.02262	0.000637	0.637274	0.637911	−17.485	177.775	160.289	−0.07827	0.83397	0.75570
−55	0.02998	0.000642	0.490358	0.491000	−13.141	175.762	162.621	−0.05815	0.80563	0.74748
−50	0.03915	0.000648	0.382457	0.383105	−8.779	173.730	164.951	−0.03841	0.77848	0.74007
−45	0.05044	0.000654	0.302029	0.302682	−4.400	171.676	167.276	−0.01903	0.75241	0.73338
−40	0.06417	0.000659	0.241251	0.241910	0	169.595	169.595	0	0.72735	0.72735
−35	0.08071	0.000666	0.194732	0.195398	4.420	167.482	171.903	0.01871	0.70322	0.72193
−30	0.10041	0.000672	0.158703	0.159375	8.862	165.335	174.197	0.03711	0.67993	0.71704
−25	0.12368	0.000679	0.130487	0.131166	13.327	163.149	176.476	0.05522	0.65742	0.71264
−20	0.15093	0.000685	0.108162	0.108847	17.816	160.920	178.736	0.07306	0.63563	0.70869
−15	0.18260	0.000693	0.090326	0.091018	22.331	158.643	180.974	0.09063	0.61450	0.70513
−10	0.21912	0.000700	0.075946	0.076646	26.874	156.314	183.188	0.10796	0.59397	0.70194
−5	0.26096	0.000708	0.064255	0.064963	31.446	153.928	185.375	0.12506	0.57400	0.69907
0	0.30861	0.000716	0.054673	0.055389	36.052	151.479	187.531	0.14196	0.55453	0.69649
5	0.36255	0.000724	0.046761	0.047485	40.694	148.961	189.654	0.15865	0.53551	0.69416
10	0.42330	0.000733	0.040180	0.040914	45.375	146.365	191.740	0.17517	0.51689	0.69206
15	0.49137	0.000743	0.034671	0.035413	50.100	143.684	193.784	0.19154	0.49862	0.69015
20	0.56729	0.000752	0.030028	0.030780	54.874	140.909	195.783	0.20777	0.48064	0.68841
25	0.65162	0.000763	0.026091	0.026854	59.702	138.028	197.730	0.22388	0.46292	0.68680
30	0.74490	0.000774	0.022734	0.023508	64.592	135.028	199.620	0.23991	0.44539	0.68530
35	0.84772	0.000786	0.019855	0.020641	69.551	131.896	201.446	0.25587	0.42800	0.68387
40	0.96065	0.000798	0.017373	0.018171	74.587	128.613	203.200	0.27179	0.41068	0.68248
45	1.08432	0.000811	0.015220	0.016032	79.712	125.160	204.872	0.28771	0.39338	0.68109
50	1.21932	0.000826	0.013344	0.014170	84.936	121.514	206.450	0.30366	0.37601	0.67967
55	1.36630	0.000841	0.011701	0.012542	90.274	117.645	207.920	0.31967	0.35849	0.67817
60	1.52592	0.000858	0.010253	0.011111	95.743	113.521	209.264	0.33580	0.34073	0.67653
65	1.69884	0.000877	0.008971	0.009847	101.362	109.099	210.460	0.35209	0.32262	0.67471

TABLA A.3SI (Continuación) *Propiedades termodinámicas del refrigerante-12 (diclorodifluorometano)*
TABLA A.3.1SI (Continuación) *R-12 saturado (unidades SI)*

Temp. °C	Presión abs. MPa, P	Volumen específico, m^3/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
		Líquido saturado v_f	Evap. v_{fg}	Vapor saturado v_g	Líquido saturado h_f	Evap. h_{fg}	Vapor saturado h_g	Líquido saturado s_f	Evap. s_{fg}	Vapor saturado s_g
70	1.88578	0.000897	0.007828	0.008725	107.155	104.326	211.481	0.36861	0.30401	0.67262
75	2.08745	0.000920	0.006802	0.007723	113.153	99.136	212.288	0.38543	0.28474	0.67017
80	2.30460	0.000946	0.005875	0.006821	119.394	93.437	212.832	0.40265	0.26457	0.66722
85	2.53802	0.000976	0.005029	0.006005	125.932	87.107	213.039	0.42040	0.24320	0.66361
90	2.78850	0.001012	0.004246	0.005258	132.841	79.961	212.802	0.43887	0.22018	0.65905
95	3.05689	0.001056	0.003508	0.004563	140.235	71.707	211.942	0.45833	0.19477	0.65310
100	3.34406	0.001113	0.002790	0.003903	148.314	61.810	210.124	0.47928	0.16564	0.64492
105	3.65093	0.001197	0.002045	0.003242	157.521	49.047	206.568	0.50285	0.12970	0.63254
110	3.97846	0.001364	0.001098	0.002462	169.550	28.444	197.995	0.53334	0.07423	0.60758
112	4.11548	0.001792	0	0.001792	183.418	0	183.418	0.56888	0	0.56888

TABLA A.3.2SI (Continuación) *Refrigerante-12 sobrecalentado (unidades SI)*

Temp. °C	v m^3/kg	h kJ/kg	s kJ/kg K	v m^3/kg	h kJ/kg	s kJ/kg K	v m^3/kg	h kJ/kg	s kJ/kg K
	0.05 MPa			0.10 MPa			0.15 MPa		
−20	0.341859	181.170	0.79172	0.167702	179.987	0.74064	—	—	—
−10	0.356228	186.889	0.81388	0.175223	185.839	0.76331	0.114826	184.753	0.73240
0	0.370509	192.705	0.83557	0.182648	191.765	0.78541	0.119980	190.800	0.75495
10	0.384717	198.614	0.85681	0.189995	197.770	0.80700	0.125051	196.906	0.77690
20	0.398864	204.617	0.87764	0.197277	203.855	0.82812	0.130053	203.077	0.79832
30	0.412960	210.710	0.89808	0.204507	210.018	0.84879	0.135000	209.314	0.81924
40	0.427014	216.891	0.91814	0.211692	216.262	0.86905	0.139900	215.621	0.83971
50	0.441031	223.160	0.93784	0.218839	222.583	0.88892	0.144761	221.998	0.85975
60	0.455018	229.512	0.95720	0.225956	228.982	0.90842	0.149589	228.446	0.87940
70	0.468980	235.946	0.97623	0.233045	235.457	0.92757	0.154391	234.963	0.89867
80	0.482919	242.460	0.99494	0.240112	242.007	0.94638	0.159168	241.549	0.91759
90	0.496839	249.050	1.01334	0.247160	248.629	0.96487	0.163926	248.204	0.93617

Temp. °C	v m^3/kg	h kJ/kg	s kJ/kg K	v m^3/kg	h kJ/kg	s kJ/kg K	v m^3/kg	h kJ/kg	s kJ/kg K
	0.20 MPa			0.25 MPa			0.30 MPa		
0	0.088609	189.805	0.73249	0.069752	188.779	0.71437	0.057150	187.718	0.69894
10	0.092550	196.020	0.75484	0.073024	195.109	0.73713	0.059984	194.173	0.72215
20	0.096419	202.281	0.77657	0.076219	201.468	0.75920	0.062735	200.636	0.74458
30	0.100229	208.597	0.79775	0.079351	207.866	0.78066	0.065419	207.119	0.76633
40	0.103990	214.971	0.81843	0.082432	214.309	0.80157	0.068049	213.635	0.78747
50	0.107710	221.405	0.83866	0.085470	220.803	0.82198	0.070636	220.191	0.80808
60	0.111397	227.902	0.85846	0.088474	227.351	0.84193	0.073186	226.793	0.82820
70	0.115056	234.462	0.87786	0.091449	233.956	0.86147	0.075706	233.444	0.84787
80	0.118691	241.087	0.89689	0.094399	240.620	0.88061	0.078200	240.147	0.86712
90	0.122305	247.775	0.91556	0.097328	247.341	0.89937	0.080673	246.904	0.88599
100	0.125902	254.525	0.93390	0.100239	254.122	0.91779	0.083127	253.716	0.90449
110	0.129484	261.338	0.95191	0.103135	260.962	0.93588	0.085566	260.582	0.92265
	0.40 MPa			0.50 MPa			0.60 MPa		
20	0.045837	198.906	0.72043	0.035646	197.077	0.70043	—	—	—
30	0.047971	205.577	0.74281	0.037464	203.963	0.72352	0.030422	202.263	0.70679
40	0.050046	212.250	0.76447	0.039215	210.810	0.74574	0.031966	209.307	0.72965
50	0.052072	218.939	0.78549	0.040912	217.643	0.76722	0.033450	216.300	0.75163
60	0.054059	225.653	0.80595	0.042566	224.479	0.78806	0.034887	223.268	0.77287
70	0.056014	232.401	0.82591	0.044185	231.330	0.80832	0.036286	230.231	0.79346
80	0.057941	239.188	0.84540	0.045775	238.206	0.82807	0.037653	237.201	0.81348
90	0.059846	246.017	0.86447	0.047341	245.112	0.84735	0.038996	244.188	0.83299
100	0.061731	252.892	0.88315	0.048886	252.054	0.86621	0.040316	251.200	0.85204
110	0.063601	259.815	0.90145	0.050415	259.035	0.88467	0.041619	258.242	0.87066
120	0.065456	266.786	0.91941	0.051929	266.057	0.90276	0.042907	265.318	0.88889
130	0.067299	273.806	0.93704	0.053430	273.123	0.92050	0.044181	272.431	0.90675
	0.70 MPa			0.80 MPa			0.90 MPa		
40	0.026761	207.732	0.71529	0.022830	206.074	0.70210	0.019744	204.320	0.68972
50	0.028100	214.903	0.73783	0.024068	213.446	0.72527	0.020912	211.921	0.71361
60	0.029387	222.017	0.75951	0.025247	220.720	0.74744	0.022012	219.373	0.73633
70	0.030632	229.099	0.78045	0.026380	227.934	0.76878	0.023062	226.730	0.75808
80	0.031843	236.171	0.80076	0.027477	235.114	0.78940	0.024073	234.028	0.77905
90	0.033028	243.244	0.82051	0.028545	242.279	0.80941	0.025051	241.290	0.79932

TABLA A.3.2SI (Continuación) *Refrigerante-12 sobrecalentado (unidades SI)*

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	0.70 MPa			0.80 MPa			0.90 MPa		
100	0.034189	250.330	0.83976	0.029588	249.443	0.82887	0.026005	248.537	0.81901
110	0.035332	257.436	0.85855	0.030612	256.616	0.84784	0.026937	255.781	0.83817
120	0.036459	264.568	0.87693	0.031619	263.806	0.86636	0.027852	263.032	0.85685
130	0.037572	271.730	0.89492	0.032612	271.019	0.88448	0.028751	270.298	0.87510
140	0.038673	278.925	0.91254	0.033592	278.259	0.90221	0.029639	277.585	0.89295
150	0.039765	286.155	0.92984	0.034563	285.529	0.91960	0.030515	284.896	0.91043
	1.00 MPa			1.20 MPa			1.40 MPa		
50	0.018366	210.317	0.70259	0.014483	206.813	0.68165	—	—	—
60	0.019410	217.970	0.72591	0.015463	214.964	0.70649	0.012579	211.613	0.68806
70	0.020397	225.485	0.74814	0.016368	222.851	0.72982	0.013448	219.984	0.71281
80	0.021341	232.910	0.76946	0.017221	230.568	0.75198	0.014247	228.059	0.73601
90	0.022251	240.278	0.79004	0.018032	238.171	0.77321	0.014997	235.940	0.75802
100	0.023133	247.612	0.80996	0.018812	245.699	0.79366	0.015710	243.692	0.77907
110	0.023993	254.931	0.82931	0.019567	253.180	0.81344	0.016393	251.355	0.79934
120	0.024835	262.246	0.84816	0.020301	260.632	0.83265	0.017053	258.961	0.81893
130	0.025661	269.567	0.86655	0.021018	268.072	0.85133	0.017695	266.530	0.83795
140	0.026474	276.902	0.88452	0.021721	275.509	0.86955	0.018321	274.078	0.85644
150	0.027275	284.255	0.90211	0.022412	282.952	0.88735	0.018934	281.618	0.87447
160	0.028068	291.632	0.91933	0.023093	290.408	0.90477	0.019535	289.158	0.89208
	1.60 MPa			1.80 MPa			2.00 MPa		
70	0.011208	216.810	0.69641	0.009406	213.208	0.67992	—	—	—
80	0.011984	225.344	0.72092	0.010187	222.363	0.70622	0.008704	219.024	0.69143
90	0.012698	233.563	0.74387	0.010884	231.007	0.73036	0.009406	228.226	0.71713
100	0.013366	241.575	0.76564	0.011525	239.332	0.75297	0.010035	236.936	0.74079
110	0.014000	249.448	0.78646	0.012126	247.446	0.77443	0.010615	245.336	0.76300
120	0.014608	257.225	0.80649	0.012697	255.417	0.79497	0.011159	253.528	0.78411
130	0.015195	264.937	0.82586	0.013244	263.288	0.81474	0.011676	261.577	0.80433
140	0.015765	272.606	0.84465	0.013772	271.090	0.83385	0.012172	269.526	0.82380
150	0.016320	280.250	0.86293	0.014284	278.847	0.85240	0.012651	277.405	0.84265

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	1.60 MPa			1.80 MPa			2.00 MPa		
160	0.016864	287.880	0.88076	0.014784	286.574	0.87045	0.013116	285.237	0.86094
170	0.017398	295.506	0.89816	0.015272	294.284	0.88805	0.013570	293.037	0.87874
180	0.017923	303.136	0.91519	0.015752	301.988	0.90524	0.014013	300.819	0.89611
	2.50 MPa			3.00 MPa			3.50 MPa		
90	0.006595	219.736	0.68284	—	—	—	—	—	—
100	0.007264	230.029	0.71081	0.005231	220.723	0.67755	—	—	—
110	0.007837	239.453	0.73573	0.005886	232.256	0.70806	0.004324	222.360	0.67559
120	0.008351	248.379	0.75873	0.006419	242.398	0.73420	0.004959	235.086	0.70840
130	0.008827	256.986	0.78035	0.006887	251.825	0.75788	0.005456	245.865	0.73548
140	0.009273	265.377	0.80091	0.007313	260.818	0.77991	0.005884	255.728	0.75965
150	0.009697	273.616	0.82062	0.007709	269.521	0.80072	0.006270	265.053	0.78195
160	0.010104	281.748	0.83961	0.008083	278.024	0.82059	0.006626	274.027	0.80291
170	0.010497	289.802	0.85799	0.008439	286.384	0.83967	0.006961	282.759	0.82284
180	0.010879	297.802	0.87584	0.008782	294.640	0.85809	0.007279	291.319	0.84194
190	0.011250	305.764	0.89322	0.009114	302.820	0.87594	0.007584	299.752	0.86035
200	0.011614	313.701	0.91018	0.009436	310.946	0.89330	0.007878	308.092	0.87816
	4.00 MPa			5.00 MPa					
120	0.003736	225.180	0.67769	0.001369	176.303	0.54710			
130	0.004325	238.691	0.71164	0.002501	216.458	0.64811			
140	0.004781	249.930	0.73918	0.003139	235.004	0.69359			
150	0.005172	260.124	0.76357	0.003585	248.416	0.72568			
160	0.005522	269.710	0.78596	0.003950	259.910	0.75253			
170	0.005845	278.903	0.80694	0.004268	270.400	0.77648			
180	0.006147	287.825	0.82685	0.004555	280.276	0.79851			
190	0.006434	296.552	0.84590	0.004821	289.740	0.81917			
200	0.006708	305.136	0.86424	0.005071	298.916	0.83877			
210	0.006972	313.614	0.88197	0.005308	307.882	0.85753			
220	0.007228	322.013	0.89917	0.005535	316.690	0.87557			
230	0.007477	330.352	0.91592	0.005753	325.380	0.89301			

TABLA A.4SI *Propiedades termodinámicas del refrigerante-22 (clorodifluorometano)*
TABLA A.4.1SI *Refrigerante-22 saturado (unidades SI)*

Temp. °C	Presión abs. MPa, P	Volumen específico, m³/kg: Líquido saturado v_f	Volumen específico, m³/kg: Evap. v_{fg}	Volumen específico, m³/kg: Vapor saturado v_g	Entalpía, kJ/kg: Líquido saturado h_f	Entalpía, kJ/kg: Evap. h_{fg}	Entalpía, kJ/kg: Vapor saturado h_g	Entropía, kJ/kg K: Líquido saturado s_f	Entropía, kJ/kg K: Evap. s_{fg}	Entropía, kJ/kg K: Vapor saturado s_g
−70	0.0205	0.000670	0.940268	0.940938	−30.607	249.425	218.818	−0.1401	1.2277	1.0876
−65	0.0280	0.000676	0.704796	0.705472	−25.658	246.925	221.267	−0.1161	1.1862	1.0701
−60	0.0375	0.000682	0.536470	0.537152	−20.652	244.354	223.702	−0.0924	1.1463	1.0540
−55	0.0495	0.000689	0.414138	0.414827	−15.585	241.703	226.117	−0.0689	1.1079	1.0390
−50	0.0644	0.000695	0.323862	0.324557	−10.456	238.965	228.509	−0.0457	1.0708	1.0251
−45	0.0827	0.000702	0.256288	0.256990	−5.262	236.132	230.870	−0.0227	1.0349	1.0122
−40	0.1049	0.000709	0.205036	0.205745	0	233.198	233.197	0	1.0002	1.0002
−35	0.1317	0.000717	0.165683	0.166400	5.328	230.156	235.484	0.0225	0.9664	0.9889
−30	0.1635	0.000725	0.135120	0.135844	10.725	227.001	237.726	0.0449	0.9335	0.9784
−25	0.2010	0.000733	0.111126	0.111859	16.191	223.727	239.918	0.0670	0.9015	0.9685
−20	0.2448	0.000741	0.092102	0.092843	21.728	220.327	242.055	0.0890	0.8703	0.9593
−15	0.2957	0.000750	0.076876	0.077625	27.334	216.798	244.132	0.1107	0.8398	0.9505
−10	0.3543	0.000759	0.064581	0.065340	33.012	213.132	246.144	0.1324	0.8099	0.9422
−5	0.4213	0.000768	0.054571	0.055339	38.762	209.323	248.085	0.1538	0.7806	0.9344
0	0.4976	0.000778	0.046357	0.047135	44.586	205.364	249.949	0.1751	0.7518	0.9269
5	0.5838	0.000789	0.039567	0.040356	50.485	201.246	251.731	0.1963	0.7235	0.9197
10	0.6807	0.000800	0.033914	0.034714	56.463	196.960	253.423	0.2173	0.6956	0.9129
15	0.7891	0.000812	0.029176	0.029987	62.523	192.495	255.018	0.2382	0.6680	0.9062
20	0.9099	0.000824	0.025179	0.026003	68.670	187.836	256.506	0.2590	0.6407	0.8997
25	1.0439	0.000838	0.021787	0.022624	74.910	182.968	257.877	0.2797	0.6137	0.8934
30	1.1919	0.000852	0.018890	0.019742	81.250	177.869	259.119	0.3004	0.5867	0.8871
35	1.3548	0.000867	0.016401	0.017269	87.700	172.516	260.216	0.3210	0.5598	0.8809
40	1.5335	0.000884	0.014251	0.015135	94.272	166.877	261.149	0.3417	0.5329	0.8746
45	1.7290	0.000902	0.012382	0.013284	100.982	160.914	261.896	0.3624	0.5058	0.8682
50	1.9423	0.000922	0.010747	0.011669	107.851	154.576	262.428	0.3832	0.4783	0.8615
55	2.1744	0.000944	0.009308	0.010252	114.905	147.800	262.705	0.4042	0.4504	0.8546
60	2.4266	0.000969	0.008032	0.009001	122.180	140.497	262.678	0.4255	0.4217	0.8472
65	2.6999	0.000997	0.006890	0.007887	129.729	132.547	262.276	0.4472	0.3920	0.8391

Temp. °C	Presión abs. MPa, P	Volumen específico, m³/kg: Líquido saturado v_f	Volumen específico, m³/kg: Evap. v_{fg}	Volumen específico, m³/kg: Vapor saturado v_g	Entalpía, kJ/kg: Líquido saturado h_f	Entalpía, kJ/kg: Evap. h_{fg}	Entalpía, kJ/kg: Vapor saturado h_g	Entropía, kJ/kg K: Líquido saturado s_f	Entropía, kJ/kg K: Evap. s_{fg}	Entropía, kJ/kg K: Vapor saturado s_g
70	2.9959	0.001030	0.005859	0.006889	137.625	123.772	261.397	0.4695	0.3607	0.8302
75	3.3161	0.001069	0.004914	0.005983	145.986	113.902	259.888	0.4927	0.3272	0.8198
80	3.6623	0.001118	0.004031	0.005149	155.011	102.475	257.486	0.5173	0.2902	0.8075
85	4.0368	0.001183	0.003175	0.004358	165.092	88.598	253.690	0.5445	0.2474	0.7918
90	4.4425	0.001282	0.002282	0.003564	177.204	70.037	247.241	0.5767	0.1929	0.7695
95	4.8835	0.001521	0.001030	0.002551	196.359	34.925	231.284	0.6273	0.0949	0.7222
96.006	4.9773	0.001906	0	0.001906	212.546	0	212.546	0.6708	0	0.6708

TABLA A.4.2SI *Refrigerante-22 sobrecalentado (unidades SI)*

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	0.05 MPa			0.10 MPa			0.15 MPa		
−40	0.440633	234.724	1.07616	0.216331	233.337	1.00523	—	—	—
−30	0.460641	240.602	1.10084	0.226754	239.359	1.03052	0.148723	238.078	0.98773
−20	0.480543	246.586	1.12495	0.237064	245.466	1.05513	0.155851	244.319	1.01288
−10	0.500357	252.676	1.14855	0.247279	251.665	1.07914	0.162879	250.631	1.03733
0	0.520095	258.874	1.17166	0.257415	257.956	1.10261	0.169823	257.022	1.06116
10	0.539771	265.180	1.19433	0.267485	264.345	1.12558	0.176699	263.496	1.08444
20	0.559393	271.594	1.21659	0.277500	270.831	1.14809	0.183516	270.057	1.10721
30	0.578970	278.115	1.23846	0.287467	277.416	1.17017	0.190284	276.709	1.12952
40	0.598507	284.743	1.25998	0.297394	284.101	1.19187	0.197011	283.452	1.15140
50	0.618011	291.478	1.28114	0.307287	290.887	1.21320	0.203702	290.289	1.17289
60	0.637485	298.319	1.30199	0.317149	297.772	1.23418	0.210362	297.220	1.19402
70	0.656935	305.265	1.32253	0.326986	304.757	1.25484	0.216997	304.246	1.21479
80	0.676362	312.314	1.34278	0.336801	311.842	1.27519	0.223608	311.368	1.23525
90	0.695771	319.465	1.36275	0.346596	319.026	1.29524	0.230200	318.584	1.25540
	0.20 MPa			0.25 MPa			0.30 MPa		
−20	0.115203	243.140	0.98184	—	—	—	—	—	—
−10	0.120647	249.574	1.00676	0.095280	248.492	0.98231	0.078344	247.382	0.96170
0	0.126003	256.069	1.03098	0.099689	255.097	1.00695	0.082128	254.104	0.98677
10	0.131286	262.633	1.05458	0.104022	261.755	1.03089	0.085832	260.861	1.01106

TABLA A.4.2SI *Refrigerante-22 sobrecalentado (unidades SI)*

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	0.20 MPa			0.25 MPa			0.30 MPa		
20	0.136509	269.273	1.07763	0.108292	268.476	1.05421	0.089469	267.667	1.03468
30	0.141681	275.992	1.10016	0.112508	275.267	1.07699	0.093051	274.531	1.05771
40	0.146809	282.796	1.12224	0.116681	282.132	1.09927	0.096588	281.460	1.08019
50	0.151902	289.686	1.14390	0.120815	289.076	1.12109	0.100085	288.460	1.10220
60	0.156963	296.664	1.16516	0.124918	296.102	1.14250	0.103550	295.535	1.12376
70	0.161997	303.731	1.18607	0.128993	303.212	1.16353	0.106986	302.689	1.14491
80	0.167008	310.890	1.20663	0.133044	310.409	1.18420	0.110399	309.924	1.16569
90	0.171999	318.139	1.22687	0.137075	317.692	1.20454	0.113790	317.241	1.18612
100	0.176972	325.480	1.24681	0.141089	325.063	1.22456	0.117164	324.643	1.20623
110	0.181931	332.912	1.26646	0.145086	332.522	1.24428	0.120522	332.129	1.22603
	0.40 MPa			0.50 MPa			0.60 MPa		
0	0.060131	252.051	0.95359	—	—	—	—	—	—
10	0.063060	259.023	0.97866	0.049355	257.108	0.95223	0.040180	255.109	0.92945
20	0.065915	266.010	1.00291	0.051751	264.295	0.97717	0.042280	262.517	0.95517
30	0.068710	273.029	1.02646	0.054081	271.483	1.00128	0.044307	269.888	0.97989
40	0.071455	280.092	1.04938	0.056358	278.690	1.02467	0.046276	277.250	1.00378
50	0.074160	287.209	1.07175	0.058590	285.930	1.04743	0.048198	284.622	1.02695
60	0.076830	294.386	1.09362	0.060786	293.215	1.06963	0.050081	292.020	1.04950
70	0.079470	301.630	1.11504	0.062951	300.552	1.09133	0.051931	299.456	1.07149
80	0.082085	308.944	1.13605	0.065090	307.949	1.11257	0.053754	306.938	1.09298
90	0.084679	316.332	1.15668	0.067206	315.410	1.13340	0.055553	314.475	1.11403
100	0.087254	323.796	1.17695	0.069303	322.939	1.15386	0.057332	322.071	1.13466
110	0.089813	331.339	1.19690	0.071384	330.539	1.17395	0.059094	329.731	1.15492
120	0.092358	338.961	1.21654	0.073450	338.213	1.19373	0.060842	337.458	1.17482
130	0.094890	346.664	1.23588	0.075503	345.963	1.21319	0.062576	345.255	1.19441
	0.70 MPa			0.80 MPa			0.90 MPa		
20	0.035487	260.667	0.93565	0.030366	258.737	0.91787	0.026355	256.713	0.90132
30	0.037305	268.240	0.96105	0.032034	266.533	0.94402	0.027915	264.760	0.92831
40	0.039059	275.769	0.98549	0.033632	274.243	0.96905	0.029397	272.670	0.95398

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	0.70 MPa			0.80 MPa			0.90 MPa		
50	0.040763	283.282	1.00910	0.035175	281.907	0.99314	0.030819	280.497	0.97859
60	0.042424	290.800	1.03201	0.036674	289.553	1.01644	0.032193	288.278	1.00230
70	0.044052	298.339	1.05431	0.038136	297.202	1.03906	0.033528	296.042	1.02526
80	0.045650	305.912	1.07606	0.039568	304.868	1.06108	0.034832	303.807	1.04757
90	0.047224	313.527	1.09732	0.040974	312.565	1.08257	0.036108	311.590	1.06930
100	0.048778	321.192	1.11815	0.042359	320.303	1.10359	0.037363	319.401	1.09052
110	0.050313	328.914	1.13856	0.043725	328.087	1.12417	0.038598	327.251	1.11128
120	0.051834	336.696	1.15861	0.045076	335.925	1.14437	0.039817	335.147	1.13162
130	0.053341	344.541	1.17832	0.046413	343.821	1.16420	0.041022	343.094	1.15158
140	0.054836	352.454	1.19770	0.047738	351.778	1.18369	0.042215	351.097	1.17119
150	0.056321	360.435	1.21679	0.049052	359.799	1.20288	0.043398	359.159	1.19047
	1.00 MPa			1.20 MPa			1.40 MPa		
30	0.024600	262.912	0.91358	—	—	—	—	—	—
40	0.025995	271.042	0.93996	0.020851	267.602	0.91411	0.017120	263.861	0.89010
50	0.027323	279.046	0.96512	0.022051	276.011	0.94055	0.018247	272.766	0.91809
60	0.028601	286.973	0.98928	0.023191	284.263	0.96570	0.019299	281.401	0.94441
70	0.029836	294.859	1.01260	0.024282	292.415	0.98981	0.020295	289.858	0.96942
80	0.031038	302.727	1.03520	0.025336	300.508	1.01305	0.021248	298.202	0.99339
90	0.032213	310.599	1.05718	0.026359	308.570	1.03556	0.022167	306.473	1.01649
100	0.033364	318.488	1.07861	0.027357	316.623	1.05744	0.023058	314.703	1.03884
110	0.034495	326.405	1.09955	0.028334	324.682	1.07875	0.023926	322.916	1.06056
120	0.035609	334.360	1.12004	0.029292	332.762	1.09957	0.024775	331.128	1.08172
130	0.036709	342.360	1.14014	0.030236	340.871	1.11994	0.025608	339.354	1.10238
140	0.037797	350.410	1.15986	0.031166	349.019	1.13990	0.026426	347.603	1.12259
150	0.038873	358.514	1.17924	0.032084	357.210	1.15949	0.027233	355.885	1.14240
160	0.039940	366.677	1.19831	0.032993	365.450	1.17873	0.028029	364.206	1.16183
	1.60 MPa			1.80 MPa			2.00 MPa		
50	0.015351	269.262	0.89689	0.013052	265.423	0.87625	—	—	—
60	0.016351	278.358	0.92461	0.014028	275.097	0.90573	0.012135	271.563	0.88729
70	0.017284	287.171	0.95068	0.014921	284.331	0.93304	0.013008	281.310	0.91612
80	0.018167	295.797	0.97546	0.015755	293.282	0.95876	0.013811	290.640	0.94292
90	0.019011	304.301	0.99920	0.016546	302.046	0.98323	0.014563	299.697	0.96821
100	0.019825	312.725	1.02209	0.017303	310.683	1.00669	0.015277	308.571	0.99232

TABLA A.4.2SI (Continuación) *Refrigerante-22 sobrecalentado (unidades SI)*

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	1.60 MPa			1.80 MPa			2.00 MPa		
110	0.020614	321.103	1.04424	0.018032	319.239	1.02932	0.015960	317.322	1.01546
120	0.021382	329.457	1.06576	0.018738	327.745	1.05123	0.016619	325.991	1.03780
130	0.022133	337.805	1.08673	0.019427	336.224	1.07253	0.017258	334.610	1.05944
140	0.022869	346.162	1.10721	0.020099	344.695	1.09329	0.017881	343.201	1.08049
150	0.023592	354.540	1.12724	0.020759	353.172	1.11356	0.018490	351.783	1.10102
160	0.024305	362.945	1.14688	0.021407	361.666	1.13340	0.019087	360.369	1.12107
170	0.025008	371.386	1.16614	0.022045	370.186	1.15284	0.019673	368.970	1.14070
180	0.025703	379.869	1.18507	0.022675	378.738	1.17193	0.020251	377.595	1.15995
	2.50 MPa			3.00 MPa			3.50 MPa		
70	0.009459	272.677	0.87476	—	—	—	—	—	—
80	0.010243	283.332	0.90537	0.007747	274.530	0.86780	0.005765	262.739	0.82489
90	0.010948	293.338	0.93332	0.008465	286.042	0.89995	0.006597	277.268	0.86548
100	0.011598	302.935	0.95939	0.009098	296.663	0.92881	0.007257	289.504	0.89872
110	0.012208	312.261	0.98405	0.009674	306.744	0.95547	0.007829	300.640	0.92818
120	0.012788	321.400	1.00760	0.010211	316.470	0.98053	0.008346	311.129	0.95520
130	0.013343	330.412	1.03023	0.010717	325.955	1.00435	0.008825	321.196	0.98049
140	0.013880	339.336	1.05210	0.011200	335.270	1.02718	0.009276	330.976	1.00445
150	0.014400	348.205	1.07331	0.011665	344.467	1.04918	0.009704	340.554	1.02736
160	0.014907	357.040	1.09395	0.012114	353.584	1.07047	0.010114	349.989	1.04940
170	0.015402	365.860	1.11408	0.012550	362.647	1.09116	0.010510	359.324	1.07071
180	0.015887	374.679	1.13376	0.012976	371.679	1.11131	0.010894	368.590	1.09138
190	0.016364	383.508	1.15303	0.013392	380.695	1.13099	0.011268	377.810	1.11151
200	0.016834	392.354	1.17192	0.013801	389.708	1.15024	0.011634	387.004	1.13115
	4.00 MPa			5.00 MPa			6.00 MPa		
90	0.005037	265.629	0.82544	—	—	—	—	—	—
100	0.005804	280.997	0.86721	0.003334	253.042	0.78005	—	—	—
110	0.006405	293.748	0.90094	0.004255	275.919	0.84064	0.002432	243.278	0.74674
120	0.006924	305.273	0.93064	0.004851	291.362	0.88045	0.003333	272.385	0.82185
130	0.007391	316.080	0.95778	0.005335	304.469	0.91337	0.003899	290.253	0.86675

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	4.00 MPa			5.00 MPa			6.00 MPa		
140	0.007822	326.422	0.98312	0.005757	316.379	0.94256	0.004345	304.757	0.90230
150	0.008226	336.446	1.00710	0.006139	327.563	0.96931	0.004728	317.633	0.93310
160	0.008610	346.246	1.02999	0.006493	338.266	0.99431	0.005071	329.553	0.96094
170	0.008978	355.885	1.05199	0.006826	348.633	1.01797	0.005386	340.849	0.98673
180	0.009332	365.409	1.07324	0.007142	358.760	1.04057	0.005680	351.715	1.01098
190	0.009675	374.853	1.09386	0.007444	368.713	1.06230	0.005958	362.271	1.03402
200	0.010009	384.240	1.11391	0.007735	378.537	1.08328	0.006222	372.602	1.05609
210	0.010335	393.593	1.13347	0.008018	388.268	1.10363	0.006477	382.764	1.07734
220	0.010654	402.925	1.15259	0.008292	397.932	1.12343	0.006722	392.801	1.09790

TABLA A.5SI *Propiedades termodinámicas del refrigerante-134a (1,1,1,2-tetrafluoroetano)*
TABLA A.5.1SI *Refrigerante-134a saturado (unidades SI)*

Temp. °C	Presión abs. MPa, P	Volumen específico, m³/kg: Líquido saturado v_f	Volumen específico, m³/kg: Evap. v_{fg}	Volumen específico, m³/kg: Vapor saturado v_g	Entalpía, kJ/kg: Líquido saturado h_f	Entalpía, kJ/kg: Evap. h_{fg}	Entalpía, kJ/kg: Vapor saturado h_g	Entropía, kJ/kg K: Líquido saturado s_f	Entropía, kJ/kg K: Evap. s_{fg}	Entropía, kJ/kg K: Vapor saturado s_g
−33	0.0737	0.000718	0.25574	0.25646	157.417	220.491	377.908	0.8346	0.9181	1.7528
−30	0.0851	0.000722	0.22330	0.22402	161.118	218.683	379.802	0.8499	0.8994	1.7493
−26.25	0.1013	0.000728	0.18947	0.19020	165.802	216.360	382.162	0.8690	0.8763	1.7453
−25	0.1073	0.000730	0.17956	0.18029	167.381	215.569	382.950	0.8754	0.8687	1.7441
−20	0.1337	0.000738	0.14575	0.14649	173.744	212.340	386.083	0.9007	0.8388	1.7395
−15	0.1650	0.000746	0.11932	0.12007	180.193	209.004	389.197	0.9258	0.8096	1.7354
−10	0.2017	0.000755	0.098454	0.099209	186.721	205.564	392.285	0.9507	0.7812	1.7319
−5	0.2445	0.000764	0.081812	0.082576	193.324	202.016	395.340	0.9755	0.7534	1.7288
0	0.2940	0.000773	0.068420	0.069193	200.000	198.356	398.356	1.0000	0.7262	1.7262
5	0.3509	0.000783	0.057551	0.058334	206.751	194.572	401.323	1.0243	0.6995	1.7239
10	0.4158	0.000794	0.048658	0.049451	213.580	190.652	404.233	1.0485	0.6733	1.7218
15	0.4895	0.000805	0.041326	0.042131	220.492	186.582	407.075	1.0725	0.6475	1.7200
20	0.5728	0.000817	0.035238	0.036055	227.493	182.345	409.838	1.0963	0.6220	1.7183
25	0.6663	0.000829	0.030148	0.030977	234.590	177.920	412.509	1.1201	0.5967	1.7168
30	0.7710	0.000843	0.025865	0.026707	241.790	173.285	415.075	1.1437	0.5716	1.7153
35	0.8876	0.000857	0.022237	0.023094	249.103	168.415	417.518	1.1673	0.5465	1.7139
40	1.0171	0.000873	0.019147	0.020020	256.539	163.282	419.821	1.1909	0.5214	1.7123

TABLA A.5SI (Continuación) *Propiedades termodinámicas del refrigerante-134a (1,1,1,2-tetrafluoroetano)*

TABLA A.5.1SI *Refrigerante-134a saturado (unidades SI)*

Temp. °C	Presión abs. MPa, P	Volumen específico, m³/kg: Líquido saturado v_f	Volumen específico, m³/kg: Evap. v_{fg}	Volumen específico, m³/kg: Vapor saturado v_g	Entalpía, kJ/kg: Líquido saturado h_f	Entalpía, kJ/kg: Evap. h_{fg}	Entalpía, kJ/kg: Vapor saturado h_g	Entropía, kJ/kg K: Líquido saturado s_f	Entropía, kJ/kg K: Evap. s_{fg}	Entropía, kJ/kg K: Vapor saturado s_g
45	1.1602	0.000890	0.016499	0.017389	264.110	157.852	421.962	1.2145	0.4962	1.7106
50	1.3180	0.000908	0.014217	0.015124	271.830	152.085	423.915	1.2381	0.4706	1.7088
55	1.4915	0.000928	0.012237	0.013166	279.718	145.933	425.650	1.2619	0.4447	1.7066
60	1.6818	0.000951	0.010511	0.011462	287.794	139.336	427.130	1.2857	0.4182	1.7040
65	1.8898	0.000976	0.008995	0.009970	296.088	132.216	428.305	1.3099	0.3910	1.7009
70	2.1169	0.001005	0.007653	0.008657	304.642	124.468	429.110	1.3343	0.3627	1.6970
75	2.3644	0.001038	0.006453	0.007491	313.513	115.939	429.451	1.3592	0.3330	1.6923
80	2.6337	0.001078	0.005368	0.006446	322.794	106.395	429.189	1.3849	0.3013	1.6862
85	2.9265	0.001128	0.004367	0.005495	332.644	95.440	428.084	1.4117	0.2665	1.6782
90	3.2448	0.001195	0.003412	0.004606	343.380	82.295	425.676	1.4404	0.2266	1.6670
95	3.5914	0.001297	0.002432	0.003729	355.834	64.984	420.818	1.4733	0.1765	1.6498
101.15	4.0640	0.001969	0	0.001969	390.977	0	390.977	1.5658	0	1.5658

TABLA A.5.2SI *Refrigerante-134a sobrecalentado*

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	0.10 MPa			0.15 MPa			0.20 MPa		
−25	0.19400	383.212	1.75058	—	—	—	—	—	—
−20	0.19860	387.215	1.76655	—	—	—	—	—	—
−10	0.20765	395.270	1.79775	0.13603	393.839	1.76058	0.10013	392.338	1.73276
0	0.21652	403.413	1.82813	0.14222	402.187	1.79171	0.10501	400.911	1.76474
10	0.22527	411.668	1.85780	0.14828	410.602	1.82197	0.10974	409.500	1.79562
20	0.23393	420.048	1.88689	0.15424	419.111	1.85150	0.11436	418.145	1.82563
30	0.24250	428.564	1.91545	0.16011	427.730	1.88041	0.11889	426.875	1.85491
40	0.25102	437.223	1.94355	0.16592	436.473	1.90879	0.12335	435.708	1.88357
50	0.25948	446.029	1.97123	0.17168	445.350	1.93669	0.12776	444.658	1.91171

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	0.10 MPa			0.15 MPa			0.20 MPa		
60	0.26791	454.986	1.99853	0.17740	454.366	1.96416	0.13213	453.735	1.93937
70	0.27631	464.096	2.02547	0.18308	463.525	1.99125	0.13646	462.946	1.96661
80	0.28468	473.359	2.05208	0.18874	472.831	2.01798	0.14076	472.296	1.99346
90	0.29303	482.777	2.07837	0.19437	482.285	2.04438	0.14504	481.788	2.01997
100	0.30136	492.349	2.10437	0.19999	491.888	2.07046	0.14930	491.424	2.04614
	0.25 MPa			0.30 MPa			0.40 MPa		
0	0.082 637	399.579	1.74284	—	—	—	—	—	—
10	0.086 584	408.357	1.77440	0.071 110	407.171	1.75637	0.051 681	404.651	1.72611
20	0.090 408	417.151	1.80492	0.074 415	416.124	1.78744	0.054 362	413.965	1.75844
30	0.094 139	425.997	1.83460	0.077 620	425.096	1.81754	0.056 926	423.216	1.78947
40	0.097 798	434.925	1.86357	0.080 748	434.124	1.84684	0.059 402	432.465	1.81949
50	0.101 401	443.953	1.89195	0.083 816	443.234	1.87547	0.061 812	441.751	1.84868
60	0.104 958	453.094	1.91980	0.086 838	452.442	1.90354	0.064 169	451.104	1.87718
70	0.108 480	462.359	1.94720	0.089 821	461.763	1.93110	0.066 484	460.545	1.90510
80	0.111 972	471.754	1.97419	0.092 774	471.206	1.95823	0.068 767	470.088	1.93252
90	0.115 440	481.285	2.00080	0.095 702	480.777	1.98495	0.071 022	479.745	1.95948
100	0.118 888	490.955	2.02707	0.098 609	490.482	2.01131	0.073 254	489.523	1.98604
110	0.122 318	500.766	2.05302	0.101 498	500.324	2.03734	0.075 468	499.428	2.01223
120	0.125 734	510.720	2.07866	0.104 371	510.304	2.06305	0.077 665	509.464	2.03809
	0.50 MPa			0.60 MPa			0.70 MPa		
20	0.042 256	411.645	1.73420	—	—	—	—	—	—
30	0.044 457	421.221	1.76632	0.036 094	419.093	1.74610	0.030 069	416.809	1.72770
40	0.046 557	430.720	1.79715	0.037 958	428.881	1.77786	0.031 781	426.933	1.76056
50	0.048 581	440.205	1.82696	0.039 735	438.589	1.80838	0.033 392	436.895	1.79187
60	0.050 547	449.718	1.85596	0.041 447	448.279	1.83791	0.034 929	446.782	1.82201
70	0.052 467	459.290	1.88426	0.043 108	457.994	1.86664	0.036 410	456.655	1.85121
80	0.054 351	468.942	1.91199	0.044 730	467.764	1.89471	0.037 848	466.554	1.87964
90	0.056 205	478.690	1.93921	0.046 319	477.611	1.92220	0.039 251	476.507	1.90743
100	0.058 035	488.546	1.96598	0.047 883	487.550	1.94920	0.040 627	486.535	1.93467
110	0.059 845	498.518	1.99235	0.049 426	497.594	1.97576	0.041 980	496.654	1.96143
120	0.061 639	508.613	2.01836	0.050 951	507.750	2.00193	0.043 314	506.875	1.98777
130	0.063 418	518.835	2.04403	0.052 461	518.026	2.02774	0.044 633	517.207	2.01372
140	0.065 184	529.187	2.06940	0.053 958	528.425	2.05322	0.045 938	527.656	2.03932

TABLA A.5.2SI (Continuación) *Refrigerante-134a sobrecalentado*

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	0.80 MPa			0.90 MPa			1.00 MPa		
40	0.027 113	424.860	1.74457	0.023 446	422.642	1.72943	0.020 473	420.249	1.71479
50	0.028 611	435.114	1.77680	0.024 868	433.235	1.76273	0.021 849	431.243	1.74936
60	0.030 024	445.223	1.80761	0.026 192	443.595	1.79431	0.023 110	441.890	1.78181
70	0.031 375	455.270	1.83732	0.027 447	453.835	1.82459	0.024 293	452.345	1.81273
80	0.032 678	465.308	1.86616	0.028 649	464.025	1.85387	0.025 417	462.703	1.84248
90	0.033 944	475.375	1.89427	0.029 810	474.216	1.88232	0.026 497	473.027	1.87131
100	0.035 180	485.499	1.92177	0.030 940	484.441	1.91010	0.027 543	483.361	1.89938
110	0.036 392	495.698	1.94874	0.032 043	494.726	1.93730	0.028 561	493.736	1.92682
120	0.037 584	505.988	1.97525	0.033 126	505.088	1.96399	0.029 556	504.175	1.95371
130	0.038 760	516.379	2.00135	0.034 190	515.542	1.99025	0.030 533	514.694	1.98013
140	0.039 921	526.880	2.02708	0.035 241	526.096	2.01611	0.031 495	525.305	2.00613
150	0.041 071	537.496	2.05247	0.036 278	536.760	2.04161	0.032 444	536.017	2.03175
	1.20 MPa			1.40 MPa			1.60 MPa		
50	0.017 243	426.845	1.72373	—	—	—	—	—	—
60	0.018 439	438.210	1.75837	0.015 032	434.079	1.73597	0.012 392	429.322	1.71349
70	0.019 530	449.179	1.79081	0.016 083	445.720	1.77040	0.013 449	441.888	1.75066
80	0.020 548	459.925	1.82168	0.017 040	456.944	1.80265	0.014 378	453.722	1.78466
90	0.021 512	470.551	1.85135	0.017 931	467.931	1.83333	0.015 225	465.145	1.81656
100	0.022 436	481.128	1.88009	0.018 775	478.790	1.86282	0.016 015	476.333	1.84695
110	0.023 329	491.702	1.90805	0.019 583	489.589	1.89139	0.016 763	487.390	1.87619
120	0.024 197	502.307	1.93537	0.020 362	500.379	1.91918	0.017 479	498.387	1.90452
130	0.025 044	512.965	1.96214	0.021 118	511.192	1.94634	0.018 169	509.371	1.93211
140	0.025 874	523.697	1.98844	0.021 856	522.054	1.97296	0.018 840	520.376	1.95908
150	0.026 691	534.514	2.01431	0.022 579	532.984	1.99910	0.019 493	531.427	1.98551
160	0.027 495	545.426	2.03980	0.023 289	543.994	2.02481	0.020 133	542.542	2.01147
170	0.028 289	556.443	2.06494	0.023 988	555.097	2.05015	0.020 761	553.735	2.03702

Temp. °C	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K	v m³/kg	h kJ/kg	s kJ/kg K
	1.80 MPa			2.0 MPa			2.50 MPa		
70	0.011 341	437.562	1.73085	0.009 581	432.531	1.71011	—	—	—
80	0.012 273	450.202	1.76717	0.010 550	446.304	1.74968	0.007 221	433.797	1.70180
90	0.013 099	462.164	1.80057	0.011 374	458.951	1.78500	0.008 157	449.499	1.74567
100	0.013 854	473.741	1.83202	0.012 111	470.996	1.81772	0.008 907	463.279	1.78311
110	0.014 560	485.095	1.86205	0.012 789	482.693	1.84866	0.009 558	476.129	1.81709
120	0.015 230	496.325	1.89098	0.013 424	494.187	1.87827	0.010 148	488.457	1.84886
130	0.015 871	507.498	1.91905	0.014 028	505.569	1.90686	0.010 694	500.474	1.87904
140	0.016 490	518.659	1.94639	0.014 608	516.900	1.93463	0.011 208	512.307	1.90804
150	0.017 091	529.841	1.97314	0.015 168	528.224	1.96171	0.011 698	524.037	1.93609
160	0.017 677	541.068	1.99936	0.015 712	539.571	1.98821	0.012 169	535.722	1.96338
170	0.018 251	552.357	2.02513	0.016 242	550.963	2.01421	0.012 624	547.399	1.99004
180	0.018 814	563.724	2.05049	0.016 762	562.418	2.03977	0.013 066	559.098	2.01614
190	0.019 369	575.177	2.07549	0.017 272	573.950	2.06494	0.013 498	570.841	2.04177
	3.0 MPa			3.50 MPa			4.0 MPa		
90	0.005 755	436.193	1.69950	—	—	—	—	—	—
100	0.006 653	453.731	1.74717	0.004 839	440.433	1.70386	—	—	—
110	0.007 339	468.500	1.78623	0.005 667	459.211	1.75355	0.004 277	446.844	1.71480
120	0.007 924	482.043	1.82113	0.006 289	474.697	1.79346	0.005 005	465.987	1.76415
130	0.008 446	494.915	1.85347	0.006 813	488.771	1.82881	0.005 559	481.865	1.80404
140	0.008 926	507.388	1.88403	0.007 279	502.079	1.86142	0.006 027	496.295	1.83940
150	0.009 375	519.618	1.91328	0.007 706	514.928	1.89216	0.006 444	509.925	1.87200
160	0.009 801	531.704	1.94151	0.008 103	527.496	1.92151	0.006 825	523.072	1.90271
170	0.010 208	543.713	1.96892	0.008 480	539.890	1.94980	0.007 181	535.917	1.93203
180	0.010 601	555.690	1.99565	0.008 839	552.185	1.97724	0.007 517	548.573	1.96028
190	0.010 982	567.670	2.02180	0.009 185	564.430	2.00397	0.007 837	561.117	1.98766
200	0.011 353	579.678	2.04745	0.009 519	576.665	2.03010	0.008 145	573.601	2.01432

TABLA A.6SI *Propiedades termodinámicas del nitrógeno*
TABLA A.6.1SI *Nitrógeno saturado (unidades SI)*

Temp. K	Presión abs. MPa P	Volumen específico, m^3/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
		Líquido saturado v_f	Evap. v_{fg}	Vapor saturado v_g	Líquido saturado h_f	Evap. h_{fg}	Vapor saturado h_g	Líquido saturado s_f	Evap. s_{fg}	Vapor saturado s_g
63.148	0.01252	0.001150	1.480099	1.481249	−150.911	215.392	64.482	2.4234	3.4108	5.8342
65	0.01741	0.001160	1.092665	1.093825	−147.172	213.384	66.212	2.4816	3.2829	5.7646
70	0.03858	0.001191	0.525015	0.526206	−137.088	207.788	70.700	2.6307	2.9683	5.5991
75	0.07610	0.001223	0.280499	0.281722	−126.949	201.816	74.867	2.7700	2.6909	5.4609
77.348	0.101325	0.001240	0.215145	0.216385	−122.150	198.839	76.689	2.8326	2.5707	5.4033
80	0.13699	0.001259	0.162485	0.163744	−116.689	195.319	78.630	2.9014	2.4415	5.3429
85	0.22903	0.001299	0.100204	0.101503	−106.252	188.149	81.898	3.0266	2.2136	5.2401
90	0.36066	0.001343	0.064803	0.066146	−95.577	180.137	84.560	3.1466	2.0016	5.1482
95	0.54082	0.001393	0.043398	0.044792	−84.593	171.075	86.482	3.2627	1.8009	5.0636
100	0.77881	0.001452	0.029764	0.031216	−73.199	160.691	87.493	3.3761	1.6070	4.9831
105	1.08423	0.001522	0.020673	0.022195	−61.238	148.597	87.359	3.4883	1.4153	4.9036
110	1.46717	0.001610	0.014342	0.015952	−48.446	134.165	85.719	3.6017	1.2197	4.8215
115	1.93875	0.001729	0.009717	0.011445	−34.308	116.212	81.904	3.7204	1.0106	4.7310
120	2.51248	0.001915	0.006083	0.007998	−17.605	91.930	74.324	3.8536	0.7661	4.6197
125	3.20886	0.002353	0.002530	0.004883	6.677	48.762	55.438	4.0395	0.3901	4.4296
126.193	3.39780	0.003194	0	0.003194	29.791	0	29.791	4.2193	0	4.2193

TABLA A.6.2SI *Nitrógeno sobrecalentado (unidades SI)*

Presión abs. MPa		Temperatura, K								
		100	125	150	175	200	225	250	275	300
0.1	v	0.291030	0.367236	0.442612	0.517577	0.592311	0.666904	0.741404	0.815839	0.890229
	h	101.938	128.423	154.695	180.860	206.967	233.039	259.090	285.128	311.160
	s	5.6944	5.9308	6.1225	6.2838	6.4232	6.5461	6.6559	6.7551	6.8457
0.2	v	0.142521	0.181711	0.220007	0.257878	0.295515	0.333008	0.370408	0.407743	0.445033
	h	100.238	127.294	153.876	180.236	206.476	232.644	258.766	284.861	310.938
	s	5.4775	5.7191	5.9130	6.0755	6.2157	6.3390	6.4491	6.5486	6.6393
0.5	v	0.053062	0.070328	0.086429	0.102059	0.117442	0.132677	0.147817	0.162892	0.177921
	h	94.460	123.776	151.376	178.349	204.998	231.458	257.799	284.063	310.276
	s	5.1660	5.4282	5.6296	5.7959	5.9383	6.0629	6.1740	6.2741	6.3653
1.0	v	—	0.033064	0.041876	0.050120	0.058093	0.065911	0.073631	0.081285	0.088893
	h	—	117.397	147.062	175.156	202.522	229.482	256.194	282.743	309.182
	s	—	5.1872	5.4039	5.5772	5.7234	5.8504	5.9630	6.0642	6.1562
2.0	v	—	0.014030	0.019541	0.024153	0.028436	0.032548	0.036558	0.040500	0.044395
	h	—	101.541	137.779	168.584	197.528	225.543	253.014	280.140	307.034
	s	—	4.8887	5.1541	5.3443	5.4989	5.6310	5.7467	5.8502	5.9438
4.0	v	—	—	0.008231	0.011185	0.013650	0.015912	0.018063	0.020145	0.022179
	h	—	—	115.595	154.672	187.417	217.740	246.800	275.098	302.898
	s	—	—	4.8379	5.0797	5.2548	5.3978	5.5203	5.6282	5.7250

TABLA A.6.2SI (Continuación) *Nitrógeno sobrecalentado (unidades SI)*

Presión abs. MPa		Temperatura, K								
		150	175	200	225	250	275	300	350	400
	v	0.004421	0.006909	0.008771	0.010412	0.011937	0.013393	0.014803	0.017532	0.020187
6.0	h	87.298	139.945	177.293	210.125	240.822	270.294	298.988	354.951	409.83
	s	4.5685	4.8956	5.0955	5.2503	5.3797	5.4921	5.5920	5.7646	5.9112
	v	0.002914	0.004861	0.006387	0.007701	0.008905	0.010042	0.011135	0.013236	0.015264
8.0	h	61.924	125.326	167.469	202.833	235.145	265.761	295.318	352.511	408.237
	s	4.3522	4.7460	4.9717	5.1385	5.2748	5.3916	5.4945	5.6709	5.8197
	v	0.002388	0.003752	0.005014	0.006112	0.007113	0.008053	0.008952	0.01067	0.01232
10.0	h	48.659	112.363	158.353	196.022	229.841	261.532	291.902	350.260	406.790
	s	4.2290	4.6233	4.8697	5.0474	5.1901	5.3109	5.4167	5.5967	5.7477
	v	0.001955	0.002598	0.003365	0.004109	0.004804	0.005461	0.006088	0.007280	0.008416
15.0	h	36.805	91.928	140.599	181.908	218.586	252.470	284.565	345.466	403.791
	s	4.0790	4.4191	4.6796	4.8745	5.0292	5.1585	5.2702	5.4581	5.6139
	v	0.001782	0.002187	0.002687	0.003213	0.003729	0.004226	0.004704	0.005617	0.006487
20.0	h	33.644	83.317	130.168	172.324	210.434	245.699	279.007	341.856	401.649
	s	3.9960	4.3024	4.5529	4.7517	4.9124	5.0469	5.1629	5.3568	5.5166

TABLA A.7SI *Propiedades termodinámicas del metano*
TABLA A.7.1SI *Metano saturado (unidades SI)*

Temp. K	Presión abs. MPa	Volumen específico, m^3/kg			Entalpía, kJ/kg			Entropía, kJ/kg K		
		Líquido saturado	Evap.	Vapor saturado	Líquido saturado	Evap.	Vapor saturado	Líquido saturado	Evap.	Vapor saturado
	P	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
		v	v	v	h	h	h	s	s	s
90.685	0.01169	0.00221	3.97955	3.98176	-358.1	543.1	185.1	4.226	5.989	10.216
95	0.01983	0.00224	2.44824	2.45048	-343.7	537.2	193.4	4.381	5.654	10.035
100	0.03441	0.00228	1.47657	1.47885	-326.8	529.8	202.9	4.554	5.298	9.851
105	0.05643	0.00231	0.93791	0.94022	-309.7	521.8	212.2	4.721	4.970	9.691
110	0.08820	0.00235	0.62219	0.62454	-292.3	513.3	221.0	4.882	4.666	9.548
115	0.13232	0.00239	0.42808	0.43048	-274.7	504.1	229.4	5.037	4.384	9.421
120	0.19158	0.00244	0.30371	0.30615	-257.0	494.2	237.2	5.187	4.118	9.305
125	0.26896	0.00249	0.22110	0.22359	-239.0	483.4	244.5	5.332	3.868	9.200
130	0.36760	0.00254	0.16448	0.16702	-220.7	471.7	251.0	5.473	3.629	9.102
135	0.49072	0.00259	0.12457	0.12717	-202.1	458.9	256.8	5.611	3.399	9.011
140	0.64165	0.00265	0.09574	0.09839	-183.2	444.8	261.7	5.746	3.177	8.924
145	0.82379	0.00272	0.07444	0.07716	-163.7	429.4	265.7	5.879	2.961	8.841
150	1.04065	0.00279	0.05838	0.06117	-143.7	412.3	268.5	6.011	2.748	8.759
155	1.29580	0.00288	0.04604	0.04892	-123.1	393.3	270.2	6.141	2.537	8.679
160	1.59296	0.00297	0.03638	0.03935	-101.6	372.0	270.3	6.272	2.325	8.597
165	1.93607	0.00309	0.02868	0.03176	-79.1	347.8	268.7	6.405	2.108	8.512
170	2.32936	0.00322	0.02241	0.02563	-55.2	320.0	264.8	6.540	1.882	8.422
175	2.77762	0.00339	0.01718	0.02058	-29.3	287.2	257.9	6.681	1.641	8.322
180	3.28655	0.00362	0.01266	0.01628	-0.5	246.8	246.2	6.833	1.371	8.204
185	3.86361	0.00398	0.00845	0.01243	33.8	192.1	225.9	7.009	1.038	8.048
190	4.52082	0.00499	0.00298	0.00796	92.2	79.8	172.0	7.305	0.420	7.725
190.551	4.59920	0.00615	0	0.00615	129.7	0	129.7	7.500	0	7.500

TABLA A.7.2SI *Metano sobrecalentado (unidades SI)*

Presión abs. MPa		Temperatura, K									
		150	175	200	225	250	275	300	350	400	450
0.05	v	1.5433	1.8054	2.0665	2.3270	2.5872	2.8472	3.1069	3.6262	4.1451	—
	h	308.5	360.8	413.2	465.8	518.9	572.9	628.1	742.9	865.4	—
	s	10.5170	10.8399	11.1196	11.3674	11.5914	11.7972	11.9891	12.3429	12.6697	—
0.10	v	0.7659	0.8984	1.0299	1.1609	1.2915	1.4219	1.5521	1.8123	2.0721	—
	h	306.8	359.6	412.2	465.0	518.3	572.4	627.6	742.6	865.1	—
	s	10.1504	10.4759	10.7570	11.0058	11.2303	11.4365	11.6286	11.9829	12.3099	—
0.50	v	0.1433	0.1726	0.2006	0.2280	0.2550	0.2817	0.3083	0.3611	0.4137	—
	h	292.3	349.1	404.1	458.5	512.9	567.8	623.7	739.6	862.8	—
	s	9.2515	9.6021	9.8959	10.1520	10.3812	10.5906	10.7850	11.1422	11.4710	—
1.00	v	0.0643	0.0815	0.0968	0.1113	0.1254	0.1392	0.1528	0.1798	0.2064	—
	h	270.6	334.9	393.5	450.1	506.0	562.0	618.8	735.9	860.0	—
	s	8.7902	9.1871	9.5006	9.7672	10.0028	10.2164	10.4138	10.7748	11.1059	—
1.50	v	—	0.0508	0.0621	0.0724	0.0822	0.0917	0.1010	0.1193	0.1373	—
	h	—	318.8	382.3	441.4	499.0	556.2	613.8	732.3	857.2	—
	s	—	8.9121	9.2514	9.5303	9.7730	9.9911	10.1916	10.5565	10.8899	—
2.00	v	—	0.0350	0.0446	0.0529	0.0606	0.0680	0.0751	0.0891	0.1027	—
	h	—	300.0	370.2	432.4	491.8	550.3	608.9	728.6	854.3	—
	s	—	8.6839	9.0596	9.3532	9.6036	9.8266	10.0303	10.3992	10.7349	—

TABLA A.7.2SI (Continuación) *Metano sobrecalentado (unidades SI)*

Presión abs. MPa		Temperatura, K									
		100	125	200	225	250	275	300	350	400	450
3.00	v	—	—	0.0269	0.0333	0.0390	0.0442	0.0492	0.0589	0.0682	0.0774
	h	—	—	342.7	413.3	477.1	538.3	598.8	721.2	848.8	983.5
	s	—	—	8.7492	9.0823	9.3512	9.5848	9.7954	10.1726	10.5130	10.8303
4.00	v	—	—	0.0176	0.0235	0.0281	0.0324	0.0363	0.0438	0.0510	0.0580
	h	—	—	308.2	392.4	461.6	526.1	588.7	713.9	843.2	979.2
	s	—	—	8.4675	8.8653	9.1574	9.4031	9.6212	10.0071	10.3523	10.6725
5.00	v	—	—	0.0114	0.0175	0.0216	0.0252	0.0286	0.0348	0.0406	0.0463
	h	—	—	258.3	369.3	445.6	513.6	578.6	706.7	837.8	975.0
	s	—	—	8.1459	8.6728	8.9945	9.2540	9.4802	9.8751	10.2251	10.5483
6.00	v	—	—	0.0061	0.0135	0.0173	0.0205	0.0234	0.0288	0.0338	0.0386
	h	—	—	160.3	343.7	428.8	500.9	568.4	699.5	832.4	970.9
	s	—	—	7.6125	8.4907	8.8502	9.1253	9.3601	9.7643	10.1192	10.4453
8.00	v	—	—	0.0041	0.0085	0.0120	0.0147	0.0171	0.0213	0.0252	0.0289
	h	—	—	88.5	285.0	393.9	475.4	548.1	685.4	822.0	962.9
	s	—	—	7.2069	8.1344	8.5954	8.9064	9.1598	9.5831	9.9477	10.2796
10.00	v	—	—	0.0038	0.0059	0.0089	0.0113	0.0133	0.0169	0.0201	0.0231
	h	—	—	72.2	229.3	358.6	450.1	528.4	671.8	811.9	955.3
	s	—	—	7.0862	7.8245	8.3716	8.7210	8.9936	9.4362	9.8104	10.1480

TABLA A.8SI *Constantes críticas (unidades SI)*

Sustancia	Fórmula	Peso molecular	Temperatura K	Presión MPa	Volumen m^3/kmol	Factor acéntrico
Amoniaco	NH_3	17.031	405.5	11.35	0.0725	0.250
Argón	Ar	39.948	150.8	4.87	0.0749	0.001
Bromo	Br_2	159.808	588	10.30	0.1272	0.108
Dióxido de carbono	CO_2	44.01	304.1	7.38	0.0939	0.239
Monóxido de carbono	CO	28.01	132.9	3.50	0.0932	0.066
Cloro	Cl_2	70.906	416.9	7.98	0.1238	0.090
Deuterio (normal)	D_2	4.032	38.4	1.66	—	−0.160
Flúor	F_2	37.997	144.3	5.22	0.0663	0.054
Helio	He	4.003	5.19	0.227	0.0574	−0.365
Helio[3]	He	3.017	3.31	0.114	0.0729	−0.473
Hidrógeno (normal)	H_2	2.016	33.2	1.30	0.0651	−0.218
Kriptón	Kr	83.80	209.4	5.50	0.0912	0.005
Neón	Ne	20.183	44.4	2.76	0.0416	−0.029
Óxido nítrico	NO	30.006	180	6.48	0.0577	0.588
Nitrógeno	N_2	28.013	126.2	3.39	0.0898	0.039
Dióxido de nitrógeno	NO_2	46.006	431	10.1	0.1678	0.834
Óxido nitroso	N_2O	44.013	309.6	7.24	0.0974	0.165
Oxígeno	O_2	31.999	154.6	5.04	0.0734	0.025
Dióxido de azufre	SO_2	64.063	430.8	7.88	0.1222	0.256
Agua	H_2O	18.015	647.3	22.12	0.0571	0.344
Xenón	Xe	131.30	289.7	5.84	0.1184	0.008
Acetileno	C_2H_2	26.038	308.3	6.14	0.1127	0.190
Benceno	C_6H_6	78.114	562.2	4.89	0.2590	0.212
n-Butano	C_3H_{10}	58.124	425.2	3.80	0.2550	0.199
Tetracloruro de carbono	CCL_4	153.823	556.4	4.56	0.2759	0.193
Clorodifluoroetano[a] (142b)	CH_3CCLF_2	100.495	410.3	4.25	0.2310	0.250
Clorodifluorometano (22)	$CHCLF_2$	86.469	369.3	4.97	0.1656	0.221
Cloroformo	$CHCL_3$	119.378	536.4	5.37	0.2389	0.218
Diclorofluorometano (12)	CCL_2F_2	120.914	385.0	4.14	0.2167	0.204
Diclorofluoroetano[a] (141)	CH_3CCL_2F	116.95	481.5	4.54	0.2520	0.215
Diclorofluorometano (21)	$CHCL_2F$	102.923	451.6	5.18	0.1964	0.210
Diclorotrifluoroetano[a] (123)	$CHCL_2CF_3$	152.93	456.9	3.67	0.2781	0.282
Difluoroetano[a] (152a)	CHF_2CH_3	66.05	386.4	4.52	0.1795	0.275
Etano	C_2H_6	30.070	305.4	4.88	0.1483	0.099
Alcohol etílico	C_2H_5OH	46.069	513.9	6.14	0.1671	0.644
Etileno	C_2H_4	28.054	282.4	5.04	0.1304	0.089
n-Heptano	C_7H_{16}	100.205	540.3	2.74	0.4320	0.349
n-Hexano	C_6H_{14}	86.178	507.5	3.01	0.3700	0.299
Metano	CH_4	16.043	190.4	4.60	0.0992	0.011
Alcohol metílico	CH_3OH	32.042	512.6	8.09	0.1180	0.556

TABLA A.8SI (Continuación) *Constantes críticas (unidades SI)*

Sustancia	Fórmula	Peso molecular	Temperatura K	Presión MPa	Volumen m^3/kmol	Factor acéntrico
Cloruro de metilo	CH_3CL	50.488	416.3	6.70	0.1389	0.153
n-Octano	C_8H_{18}	114.232	568.8	2.49	0.4920	0.398
n-Pentano	C_5H_{16}	72.151	469.7	3.37	0.3040	0.251
Propano	C_3H_8	44.094	369.8	4.25	0.2030	0.153
Propeno	C_3H_6	42.081	364.9	4.60	0.1810	0.144
Propino	C_3H_4	40.065	402.4	5.63	0.1640	0.215
Tetrafluoroetano[a] (134a)	CF_3CH_2F	102.03	374.2	4.06	0.1980	0.327

Fuente: R. C. Reid, J. M. Prausnitz and B. E. Poling. *The properties of gases and liquids*, fourth edition, McGraw-Hill Book Company, New York.

[a] Datos de M. O. McLinden, NIST Thermophysics Division, 1989.

TABLA A.9SI *Propiedades de diversos sólidos y líquidos a 25°C (unidades SI)*

Sólido	C_p kJ/kg K	ρ, kg/m^3	Líquido	C_p kJ/kg K	ρ, kg/m^3
Aluminio	0.9	2700	Amoniaco	4.8	602
Concreto	0.65	2300	Benceno	1.72	879
Cobre	0.386	8900	Butano	2.469	556
Vidrio	0.8	2300	Etanol	2.456	783
Granito	1.017	2700	Glicerina	2.40	1200
Grafito	0.711	2500	Iso-octano	2.1	692
Hierro	0.450	7840	Mercurio	0.139	13560
Plomo	0.128	11310	Metanol	2.55	787
Hule (blando)	1.84	1100	Petróleo (ligero)	1.8	910
Arena (seca)	0.8	1450-1750	Propano	2.54	510
Plata	0.235	10470	R-12	0.971	1310
Acero (AISI302)	0.48	8050	R-134a	1.43	1206
Estaño	0.217	5730	Agua	4.184	997
Madera (la mayoría)	1.76	350-700			

TABLA A.10SI *Propiedades de diversos gases ideales a 300 K (unidades SI)*

Gas	Fórmula química	Masa molecular	R kJ/kg K	C_{po} kJ/kg K	C_{vo} kJ/kg K	k
Acetileno	C_2H_2	26.038	0.3193	1.6986	1.3793	1.231
Aire		28.97	0.2870	1.0035	0.7165	1.400
Amoniaco	NH_3	17.031	0.48819	2.1300	1.6418	1.297
Argón	Ar	39.948	0.20813	0.5203	0.3122	1.667
Butano	C_4H_{10}	58.124	0.14304	1.7164	1.5734	1.091
Dióxido de carbono	CO_2	44.01	0.18892	0.8418	0.6529	1.289
Monóxido de carbono	CO	28.01	0.29683	1.0413	0.7445	1.400

TABLA A.10SI (Continuación) *Propiedades de diversos gases ideales a 300 K (unidades SI)*

Gas	Fórmula química	Masa molecular	R kJ/kg K	C_{po} kJ/kg K	C_{vo} kJ/kg K	k
Etano	C_2H_6	30.07	0.27650	1.7662	1.4897	1.186
Etanol	C_2H_5OH	46.069	0.18048	1.427	1.246	1.145
Etileno	C_2H_4	28.054	0.29637	1.5482	1.2518	1.237
Helio	He	4.003	2.07703	5.1926	3.1156	1.667
Hidrógeno	H_2	2.016	4.12418	14.2091	10.0849	1.409
Metano	CH_4	16.04	0.51835	2.2537	1.7354	1.299
Metanol	CH_3OH	32.042	0.25948	1.4050	1.1455	1.227
Neón	Ne	20.183	0.41195	1.0299	0.6179	1.667
Nitrógeno	N_2	28.013	0.29680	1.0416	0.7448	1.400
Óxido nitroso	N_2O	44.013	0.18891	0.8793	0.6904	1.274
n-Octano	C_8H_{18}	114.23	0.07279	1.7113	1.6385	1.044
Oxígeno	O_2	31.999	0.25983	0.9216	0.6618	1.393
Propano	C_3H_8	44.097	0.18855	1.6794	1.4909	1.126
Vapor	H_2O	18.015	0.46152	1.8723	1.4108	1.327
Dióxido de azufre	SO_2	64.059	0.12979	0.6236	0.4938	1.263
Trióxido de azufre	SO_3	80.058	0.10386	0.6346	0.5307	1.196

TABLA A.11SI *Calores específicos a presión constante de diversos gases ideales (unidades SI)*

C_{p0} = kJ/kmol K $\theta = T(\text{Kelvin})/100$

Gas		Intervalo K	Error máximo %
N_2	$\overline{C}_{p0} = 39.060 - 512.79\,\theta^{-1.5} + 10.72.7\,\theta^{-2} - 820.40\,\theta^{-3}$	300–3500	0.43
O_2	$\overline{C}_{p0} = 37.432 + 0.020\,102\,\theta^{1.5} - 178.57\,\theta^{-1.5} + 236.88\,\theta^{-2}$	300–3500	0.30
H_2	$\overline{C}_{p0} = 56.505 - 702.74\,\theta^{-0.75} + 1165.0\,\theta^{-1} - 560.70\,\theta^{-1.5}$	300–3500	0.60
CO	$\overline{C}_{p0} = 69.145 - 0.704\,63\,\theta^{0.75} - 200.77\,\theta^{-0.5} + 176.76\,\theta^{-0.75}$	300–3500	0.42
OH	$\overline{C}_{p0} = 81.546 - 59.350\,\theta^{0.25} + 17.329\,\theta^{-0.75} - 4.2660\,\theta$	300–3500	0.43
NO	$\overline{C}_{p0} = 59.283 - 1.7096\,\theta^{0.5} - 70.613\,\theta^{-0.5} + 74.889\,\theta^{-1.5}$	300–3500	0.34
H_2O	$\overline{C}_{p0} = 143.05 - 183.54\,\theta^{0.25} + 82.751\,\theta^{0.5} - 3.6989\,\theta$	300–3500	0.43
CO_2	$\overline{C}_{p0} = -3.7357 + 30.529\,\theta^{0.5} - 4.1034\,\theta + 0.024\,198\,\theta^{2}$	300–3500	0.19
NO_2	$\overline{C}_{p0} = 46.045 + 216.10\,\theta^{-0.5} - 363.66\,\theta^{-0.75} + 232.550\,\theta^{-2}$	300–3500	0.26
CH_4	$\overline{C}_{p0} = -672.87 + 439.74\,\theta^{0.25} - 24.875\,\theta^{0.75} + 323.88\,\theta^{-0.5}$	300–2000	0.15
C_2H_4	$\overline{C}_{p0} = -95.395 + 123.15\,\theta^{0.5} - 35.641\,\theta^{0.75} + 182.77\,\theta^{-3}$	300–2000	0.07
C_2H_6	$\overline{C}_{p0} = 6.895 + 17.26\,\theta - 0.6402\,\theta^{2} + 0.007\,28\,\theta^{3}$	300–1500	0.83
C_3H_8	$\overline{C}_{p0} = -4.042 + 30.46\,\theta - 1.571\,\theta^{2} + 0.031\,71\,\theta^{3}$	300–1500	0.40
C_4H_{10}	$\overline{C}_{p0} = 3.954 + 37.12\,\theta - 1.833\,\theta^{2} + 0.034\,98\,\theta^{3}$	300–1500	0.54

Fuente: Tomado de T. C. Scott and R. E. Sonntag, University of Michigan, documento inédito 1971, excepto C_2H_6, C_3H_8 y C_4H_{10} que provienen de K. A. Kobe, Petroleum Refiner, 28, No. 2, 113 (1949).

TABLA A.12SI *Propiedades del aire como gas ideal, entropía estándar en unidades SI a la presión de 0.1 MPa (1 bar)*

T K	u kJ/kg	h kJ/kg	s° kJ/kg K	P_r	v_r
200	142.768	200.174	6.46260	0.27027	493.466
220	157.071	220.218	6.55812	0.37700	389.150
240	171.379	240.267	6.64535	0.51088	313.274
260	185.695	260.323	6.72562	0.67573	256.584
280	200.022	280.390	6.79998	0.87556	213.257
290	207.191	290.430	6.83521	0.98990	195.361
298.15	213.036	298.615	6.86305	1.09071	182.288
300	214.364	300.473	6.86926	1.11458	179.491
320	228.726	320.576	6.93413	1.39722	152.728
340	243.113	340.704	6.99515	1.72814	131.200
360	257.532	360.863	7.05276	2.11226	113.654
380	271.988	381.060	7.10735	2.55479	99.1882
400	286.487	401.299	7.15926	3.06119	87.1367
420	301.035	421.589	7.20875	3.63727	77.0025
440	315.640	441.934	7.25607	4.28916	68.4088
460	330.306	462.340	7.30142	5.02333	61.0658
480	345.039	482.814	7.34499	5.84663	54.7479
500	359.844	503.360	7.38692	6.76629	49.2777
520	374.726	523.982	7.42736	7.78997	44.5143
540	389.689	544.686	7.46642	8.92569	40.3444
560	404.736	565.474	7.50422	10.18197	36.6765
580	419.871	586.350	7.54084	11.56771	33.4358
600	435.097	607.316	7.57638	13.09232	30.5609
620	450.415	628.375	7.61090	14.76564	28.0008
640	465.828	649.528	7.64448	16.59801	25.7132
660	481.335	670.776	7.67717	18.60025	23.6623
680	496.939	692.120	7.70903	20.78367	21.8182
700	512.639	713.561	7.74010	23.16010	20.1553
720	528.435	735.098	7.77044	25.74188	18.6519
740	544.328	756.731	7.80008	28.54188	17.2894
760	560.316	778.460	7.82905	31.57347	16.0518
780	576.400	800.284	7.85740	34.85061	14.9250
800	592.577	822.202	7.88514	38.38777	13.8972
850	633.422	877.397	7.95207	48.46828	11.6948
900	674.824	933.152	8.01581	60.51977	9.91692
950	716.756	989.436	8.07667	74.81519	8.46770
1000	759.189	1046.221	8.13493	91.65077	7.27604
1050	802.095	1103.478	8.19081	111.3467	6.28845
1100	845.445	1161.180	8.24449	134.2478	5.46408
1150	881.211	1219.298	8.29616	160.7245	4.77141

TABLA A.12SI (Continuación) *Propiedades del aire como gas ideal, entropía estándar en unidades SI a la presión de 0.1 MPa (1 bar)*

T K	u kJ/kg	h kJ/kg	s° kJ/kg K	P_r	v_r
1100	845.445	1161.180	8.24449	134.2478	5.46408
1120	862.903	1184.379	8.26539	144.3878	5.17272
1140	880.426	1207.642	8.28598	155.1245	4.90068
1160	898.012	1230.969	8.30626	166.4834	4.64642
1180	915.660	1254.357	8.32625	178.4908	4.40857
1200	933.367	1277.805	8.34596	191.1736	4.18586
1250	977.888	1336.677	8.39402	226.0192	3.68804
1300	1022.751	1395.892	8.44046	265.7145	3.26257
1350	1067.936	1455.429	8.48539	310.7426	2.89711
1400	1113.426	1515.270	8.52891	361.6192	2.58171
1450	1159.202	1575.398	8.57111	418.8942	2.30831
1500	1205.253	1635.800	8.61208	483.1554	2.07031
1550	1251.547	1696.446	8.65185	554.9577	1.86253
1600	1298.079	1757.329	8.69051	634.9670	1.68035
1650	1344.834	1818.436	8.72811	723.8560	1.52007
1700	1391.801	1879.755	8.76472	822.3320	1.37858
1750	1438.970	1941.275	8.80039	931.1376	1.25330
1800	1486.331	2002.987	8.83516	1051.051	1.14204
1850	1533.873	2064.882	8.86908	1182.888	1.04294
1900	1581.591	2126.951	8.90219	1327.498	0.95445
1950	1629.474	2189.186	8.93452	1485.772	0.87521
2000	1677.518	2251.581	8.96611	1658.635	0.80410
2050	1725.714	2314.128	8.99699	1847.077	0.74012
2100	1774.057	2376.823	9.02721	2052.109	0.68242
2150	1822.541	2439.659	9.05678	2274.789	0.63027
2200	1871.161	2502.630	9.08573	2516.217	0.58305
2250	1919.912	2565.733	9.11409	2777.537	0.54020
2300	1968.790	2628.962	9.14189	3059.939	0.50124
2350	2017.789	2692.313	9.16913	3364.658	0.46576
2400	2066.907	2755.782	9.19586	3692.974	0.43338
2450	2116.138	2819.366	9.22208	4046.215	0.40378
2500	2165.480	2883.059	9.24781	4425.759	0.37669
2550	2214.929	2946.859	9.27308	4833.031	0.35185
2600	2264.481	3010.763	9.29790	5269.505	0.32903
2650	2314.133	3074.767	9.32228	5736.707	0.30805
2700	2363.883	3138.868	9.34625	6236.215	0.28872
2750	2413.727	3203.064	9.36980	6769.657	0.27089
2800	2463.663	3267.351	9.39297	7338.715	0.25443
2850	2513.687	3331.726	9.41576	7945.124	0.23921
2900	2563.797	3396.188	9.43818	8590.676	0.22511
2950	2613.990	3460.733	9.46025	9277.216	0.21205
3000	2664.265	3525.359	9.48198	10006.645	0.19992

TABLA A.13SI *Propiedades de diversas sustancias como gases ideales (unidades SI), entropías a la presión de 0.1 MPa (1 bar)*

	Nitrógeno, diatómico (N_2) $\bar{h}^\circ_{f,298} = 0$ kJ/kmol $M = 28.013$		Nitrógeno, monoatómico (N) $\bar{h}^\circ_{f,298} = 472\,680$ kJ/kmol $M = 14.007$	
T K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K
0	−8670	0	−6197	0
100	−5768	159.812	−4119	130.593
200	−2857	179.985	−2040	145.001
298	0	191.609	0	153.300
300	54	191.789	38	153.429
400	2971	200.181	2117	159.409
500	5911	206.740	4196	164.047
600	8894	212.177	6274	167.837
700	11937	216.865	8353	171.041
800	15046	221.016	10431	173.816
900	18223	224.757	12510	176.265
1000	21463	228.171	14589	178.455
1100	24760	231.314	16667	180.436
1200	28109	234.227	18746	182.244
1300	31503	236.943	20825	183.908
1400	34936	239.487	22903	185.448
1500	38405	241.881	24982	186.883
1600	41904	244.139	27060	188.224
1700	45430	246.276	29139	189.484
1800	48979	248.304	31218	190.672
1900	52549	250.234	33296	191.796
2000	56137	252.075	35375	192.863
2200	63362	255.518	39534	194.845
2400	70640	258.684	43695	196.655
2600	77963	261.615	47860	198.322
2800	85323	264.342	52033	199.868
3000	92715	266.892	56218	201.311
3200	100134	269.286	60420	202.667
3400	107577	271.542	64646	203.948
3600	115042	273.675	68902	205.164
3800	122526	275.698	73194	206.325
4000	130027	277.622	77532	207.437
4400	145078	281.209	86367	209.542
4800	160188	284.495	95457	211.519
5200	175352	287.530	104843	213.397
5600	190572	290.349	114550	215.195
6000	205848	292.984	124590	216.926

TABLA A.13SI (Continuación) ***Propiedades de diversas sustancias como gases ideales (unidades SI), entropías a la presión de 0.1 MPa (1 bar)***

	Oxígeno, diatómico (O_2) $\bar{h}^\circ_{f,298} = 0$ kJ/kmol $M = 31.999$		Oxígeno, monoatómico (O) $\bar{h}^\circ_{f,298} = 249\,170$ kJ/kmol $M = 16.00$	
T K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K
0	−8683	0	−6725	0
100	−5777	173.308	−4518	135.947
200	−2868	193.483	−2186	152.153
298	0	205.148	0	161.059
300	54	205.329	41	161.194
400	3027	213.873	2207	167.431
500	6086	220.693	4343	172.198
600	9245	226.450	6462	176.060
700	12499	231.465	8570	179.310
800	15836	235.920	10671	182.116
900	19241	239.931	12767	184.585
1000	22703	243.579	14860	186.790
1100	26212	246.923	16950	188.783
1200	29761	250.011	19039	190.600
1300	33345	252.878	21126	192.270
1400	36958	255.556	23212	193.816
1500	40600	258.068	25296	195.254
1600	44267	260.434	27381	196.599
1700	47959	262.673	29464	197.862
1800	51674	264.797	31547	199.053
1900	55414	266.819	33630	200.179
2000	59176	268.748	35713	201.247
2200	66770	272.366	39878	203.232
2400	74453	275.708	44045	205.045
2600	82225	278.818	48216	206.714
2800	90080	281.729	52391	208.262
3000	98013	284.466	56574	209.705
3200	106022	287.050	60767	211.058
3400	114101	289.499	64971	212.332
3600	122245	291.826	69190	213.538
3800	130447	294.043	73424	214.682
4000	138705	296.161	77675	215.773
4400	155374	300.133	86234	217.812
4800	172240	303.801	94873	219.691
5200	189312	307.217	103592	221.435
5600	206618	310.423	112391	223.066
6000	224210	313.457	121264	224.597

TABLA A.13SI (Continuación) ***Propiedades de diversas sustancias como gases ideales (unidades SI), entropías a la presión de 0.1 MPa (1 bar)***

	Dióxido de carbono (CO_2) $\bar{h}^\circ_{f,298} = -393\,522$ kJ/kmol $M = 44.01$		Monóxido de carbono (CO) $\bar{h}^\circ_{f,298} = -110\,527$ kJ/kmol $M = 28.01$	
T K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K
0	−9364	0	−8671	0
100	−6457	179.010	−5772	165.852
200	−3413	199.976	−2860	186.024
298	0	213.794	0	197.651
300	69	214.024	54	197.831
400	4003	225.314	2977	206.240
500	8305	234.902	5932	212.833
600	12906	243.284	8942	218.321
700	17754	250.752	12021	223.067
800	22806	257.496	15174	227.277
900	28030	263.646	18397	231.074
1000	33397	269.299	21686	234.538
1100	38885	274.528	25031	237.726
1200	44473	279.390	28427	240.679
1300	50148	283.931	31867	243.431
1400	55895	288.190	35343	246.006
1500	61705	292.199	38852	248.426
1600	67569	295.984	42388	250.707
1700	73480	299.567	45948	252.866
1800	79432	302.969	49529	254.913
1900	85420	306.207	53128	256.860
2000	91439	309.294	56743	258.716
2200	103562	315.070	64012	262.182
2400	115779	320.384	71326	265.361
2600	128074	325.307	78679	268.302
2800	140435	329.887	86070	271.044
3000	152853	334.170	93504	273.607
3200	165321	338.194	100962	276.012
3400	177836	341.988	108440	278.279
3600	190394	345.576	115938	280.422
3800	202990	348.981	123454	282.454
4000	215624	352.221	130989	284.387
4400	240992	358.266	146108	287.989
4800	266488	363.812	161285	291.290
5200	292112	368.939	176510	294.337
5600	317870	373.711	191782	297.167
6000	343782	378.180	207105	299.809

TABLA A.13SI (Continuación) ***Propiedades de diversas sustancias como gases ideales (unidades SI), entropías a la presión de 0.1 MPa (1 bar)***

	Agua (H_2O) $\bar{h}^\circ_{f,298} = -241\,826$ kJ/kmol $M = 18.015$		Hidróxilo (OH) $\bar{h}^\circ_{f,298} = 38\,987$ kJ/kmol $M = 17.007$	
T K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K
0	−9904	0	−9172	0
100	−6617	152.386	−6140	149.591
200	−3282	175.488	−2975	171.592
298	0	188.835	0	183.709
300	62	189.043	55	183.894
400	3450	198.787	3034	192.466
500	6922	206.532	5991	199.066
600	10499	213.051	8943	204.448
700	14190	218.739	11902	209.008
800	18002	223.826	14881	212.984
900	21937	228.460	17889	216.526
1000	26000	232.739	20935	219.735
1100	30190	236.732	24024	222.680
1200	34506	240.485	27159	225.408
1300	38941	244.035	30340	227.955
1400	43491	247.406	33567	230.347
1500	48149	250.620	36838	232.604
1600	52907	253.690	40151	234.741
1700	57757	256.631	43502	236.772
1800	62693	259.452	46890	238.707
1900	67706	262.162	50311	240.556
2000	72788	264.769	53763	242.328
2200	83153	269.706	60751	245.659
2400	93741	274.312	67840	248.743
2600	104520	278.625	75018	251.614
2800	115463	282.680	82268	254.301
3000	126548	286.504	89585	256.825
3200	137756	290.120	96960	259.205
3400	149073	293.550	104388	261.456
3600	160484	296.812	111864	263.592
3800	171981	299.919	119382	265.625
4000	183552	302.887	126940	267.563
4400	206892	308.448	142165	271.191
4800	230456	313.573	157522	274.531
5200	254216	318.328	173002	277.629
5600	278161	322.764	188598	280.518
6000	302295	326.926	204309	283.227

TABLA A.13SI (Continuación) ***Propiedades de diversas sustancias como gases ideales (unidades SI), entropías a la presión de 0.1 MPa (1 bar)***

	Hidrógeno (H_2) $\bar{h}^\circ_{f,298} = 0$ kJ/kmol $M = 2.016$		Hidrógeno monoatómico (H) $\bar{h}^\circ_{f,298} = 217\,999$ kJ/kmol $M = 1.008$	
T K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K
0	−8467	0	−6197	0
100	−5467	100.727	−4119	92.009
200	−2774	119.410	−2040	106.417
298	0	130.678	0	114.716
300	53	130.856	38	114.845
400	2961	139.219	2117	120.825
500	5883	145.738	4196	125.463
600	8799	151.078	6274	129.253
700	11730	155.609	8353	132.457
800	14681	159.554	10431	135.233
900	17657	163.060	12510	137.681
1000	20663	166.225	14589	139.871
1100	23704	169.121	16667	141.852
1200	26785	171.798	18746	143.661
1300	29907	174.294	20825	145.324
1400	33073	176.637	22903	146.865
1500	36281	178.849	24982	148.299
1600	39533	180.946	27060	149.640
1700	42826	182.941	29139	150.900
1800	46160	184.846	31218	152.089
1900	49532	186.670	33296	153.212
2000	52942	188.419	35375	154.279
2200	59865	191.719	39532	156.260
2400	66915	194.789	43689	158.069
2600	74082	197.659	47847	159.732
2800	81355	200.355	52004	161.273
3000	88725	202.898	56161	162.707
3200	96187	205.306	60318	164.048
3400	103736	207.593	64475	165.308
3600	111367	209.773	68633	166.497
3800	119077	211.856	72790	167.620
4000	126864	213.851	76947	168.687
4400	142658	217.612	85261	170.668
4800	158730	221.109	93576	172.476
5200	175057	224.379	101890	174.140
5600	191607	227.447	110205	175.681
6000	208332	230.322	118519	177.114

TABLA A.13SI (Continuación) *Propiedades de diversas sustancias como gases ideales (unidades SI), entropías a la presión de 0.1 MPa (1 bar)*

	Óxido nítrico (NO) $\bar{h}^\circ_{f,298}$ = 90 291 kJ/kmol M = 30.006		Dióxido de nitrógeno (NO_2) $\bar{h}^\circ_{f,298}$ = 33 100 kJ/kmol M = 46.005	
T K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K	$(\bar{h}-\bar{h}^\circ_{298})$ kJ/kmol	$\bar{s}^\circ$ kJ/kmol K
0	−9192	0	−10186	0
100	−6073	177.031	−6861	202.563
200	−2951	198.747	−3495	225.852
298	0	210.759	0	240.034
300	55	210.943	68	240.263
400	3040	219.529	3927	251.342
500	6059	226.263	8099	260.638
600	9144	231.886	12555	268.755
700	12308	236.762	17250	275.988
800	15548	241.088	22138	282.513
900	18858	244.985	27180	288.450
1000	22229	248.536	32344	293.889
1100	25653	251.799	37606	298.904
1200	29120	254.816	42946	303.551
1300	32626	257.621	48351	307.876
1400	36164	260.243	53808	311.920
1500	39729	262.703	59309	315.715
1600	43319	265.019	64846	319.289
1700	46929	267.208	70414	322.664
1800	50557	269.282	76008	325.861
1900	54201	271.252	81624	328.898
2000	57859	273.128	87259	331.788
2200	65212	276.632	98578	337.182
2400	72606	279.849	109948	342.128
2600	80034	282.822	121358	346.695
2800	87491	285.585	132800	350.934
3000	94973	288.165	144267	354.890
3200	102477	290.587	155756	358.597
3400	110000	292.867	167262	362.085
3600	117541	295.022	178783	365.378
3800	125099	297.065	190316	368.495
4000	132671	299.007	201860	371.456
4400	147857	302.626	224973	376.963
4800	163094	305.940	248114	381.997
5200	178377	308.998	271276	386.632
5600	193703	311.838	294455	390.926
6000	209070	314.488	317648	394.926

TABLA A.14 *Segundo y tercero coeficientes viriales reducidos y constantes de fuerza para el potencial de Lennard-Jones (6-12)*

TABLA A.14.1

Segundo y tercero coeficientes reducidos y sus derivadas

T^*	B^*	$B_1^* = T^* \frac{dB^*}{dT^*}$	C^*	$C_1^* = T^* \frac{dC^*}{dT^*}$
0.3	−27.88061	76.60701		
0.4	−13.79885	30.26698		
0.5	−8.72022	16.92367		
0.6	−6.19798	11.24883		
0.7	−4.71004	8.25711	−3.44223	29.02471
0.8	−3.73423	6.45414	−0.87753	11.80911
0.9	−3.04712	5.26492	0.06579	5.05023
1.0	−2.53809	4.42826	0.42600	2.12100
1.1	−2.14638	3.81063	0.55670	0.76761
1.2	−1.83595	3.33749	0.59235	0.12051
1.3	−1.58411	2.96421	0.58821	−0.18965
1.4	−1.37585	2.66262	0.56823	−0.33189
1.5	−1.20089	2.41414	0.54307	−0.38813
1.6	−1.05191	2.20602	0.51748	−0.39994
1.7	−0.92362	2.02926	0.49348	−0.38906
1.8	−0.81203	1.87733	0.47183	−0.36719
1.9	−0.71415	1.74537	0.45267	−0.34065
2.0	−0.62763	1.62972	0.43590	−0.31290
2.2	−0.48171	1.43663	0.40861	−0.26013
2.4	−0.36358	1.28190	0.38797	−0.21492
2.6	−0.26613	1.15517	0.37228	−0.17792
2.8	−0.18451	1.04948	0.36022	−0.14821
3.0	−0.11523	0.96000	0.35084	−0.12454
3.2	−0.05579	0.88328	0.34342	−0.10574
3.4	−0.00428	0.81676	0.33748	−0.09081
3.6	0.04072	0.75854	0.33264	−0.07895
3.8	0.08033	0.70716	0.32863	−0.06955
4.0	0.11542	0.66148	0.32526	−0.06209
4.2	0.14668	0.62060	0.32238	−0.05619
4.4	0.17469	0.58381	0.31988	−0.05154
4.6	0.19990	0.55051	0.31767	−0.04789
4.8	0.22268	0.52024	0.31569	−0.04506
5.0	0.24334	0.49260	0.31390	−0.04288
6.0	0.32290	0.38397	0.30661	−0.03831
7.0	0.37609	0.30826	0.30069	−0.03899
8.0	0.41343	0.25248	0.29533	−0.04152
9.0	0.44060	0.20970	0.29027	−0.04456
10.0	0.46088	0.17587	0.28541	−0.04758
20.0	0.52538	0.02866	0.24609	−0.06402
30.0	0.52693	-0.01749	0.21930	−0.06728

TABLA A.14.2

Constantes de fuerza a partir de los datos de coeficientes viriales experimentales

Sustancia	ε/k, K	b_0, m^3/kmol
Ne	35.8	0.0262
Ar	119.0	0.0502
Kr	173.0	0.0583
Xe	225.3	0.0854
N_2	95.05	0.0635
O_2	117.5	0.0578
CO	100.2	0.0675
NO	131.0	0.0402
CO_2	186.0	0.118
N_2O	193.0	0.118
CH_4	148.1	0.0698
CF_4	152.0	0.131

TABLA A.15 *Tablas generalizadas del factor de compresibilidad con tres parámetros (T_r, P_r, ω).*
TABLA A.15.1 *Presión de saturación generalizada, factor de compresiblidad, desviación de la entalpía, desviación de la entropía, coeficiente de fugacidad de un fluido simple*

T_r	$\ln(P_r)$	Z_f	Z_g	$\left(\frac{h^*-h}{RT_c}\right)_f$	$\left(\frac{h^*-h}{RT_c}\right)_g$	$\left(\frac{s_p^*-s_p}{R}\right)_f$	$\left(\frac{s_p^*-s_p}{R}\right)_g$	$\ln\left(\frac{f}{P}\right)$
0.30	−13.14053	0.00000	0.99998	6.04616	0.00002	20.09953	0.00005	−0.00002
0.32	−11.89025	0.00000	0.99993	5.99061	0.00007	18.06562	0.00014	−0.00007
0.34	−10.79655	0.00001	0.99983	5.93515	0.00018	16.51869	0.00035	−0.00017
0.36	−9.83281	0.00002	0.99963	5.87895	0.00040	16.01837	0.00076	−0.00037
0.38	−8.97801	0.00003	0.99927	5.82177	0.00085	15.31191	0.00150	−0.00073
0.40	−8.21540	0.00006	0.99865	5.76367	0.00163	14.41129	0.00272	−0.00134
0.42	−7.53140	0.00012	0.99770	5.70481	0.00291	13.58378	0.00463	−0.00230
0.44	−6.91492	0.00022	0.99628	5.64539	0.00489	12.82092	0.00741	−0.00371
0.46	−6.35683	0.00038	0.99430	5.58558	0.00781	12.13784	0.01129	−0.00568
0.48	−5.84950	0.00061	0.99165	5.52553	0.01191	11.50344	0.01648	−0.00832
0.50	−5.38653	0.00095	0.98820	5.46534	0.01745	10.91801	0.02317	−0.01173
0.52	−4.96253	0.00141	0.98389	5.40509	0.02472	10.37636	0.03155	−0.01600
0.54	−4.57289	0.00204	0.97862	5.34481	0.03399	9.87361	0.04176	−0.02118
0.56	−4.21367	0.00286	0.97233	5.28447	0.04552	9.40554	0.05395	−0.02734
0.58	−3.88146	0.00390	0.96498	5.22403	0.05958	8.96810	0.06823	−0.03449
0.60	−3.57331	0.00521	0.95652	5.16343	0.07641	8.55883	0.08470	−0.04265
0.62	−3.28666	0.00682	0.94695	5.10255	0.09626	8.17415	0.10344	−0.05182
0.64	−3.01926	0.00877	0.93623	5.04126	0.11938	7.81156	0.12455	−0.06198
0.66	−2.76913	0.01110	0.92436	4.97940	0.14601	7.46873	0.14811	−0.07312
0.68	−2.53452	0.01384	0.91133	4.91678	0.17640	7.14358	0.17423	−0.08519
0.70	−2.31388	0.01705	0.89711	4.85318	0.21084	6.83415	0.20302	−0.09817
0.72	−2.10584	0.02077	0.88170	4.78832	0.24961	6.53867	0.23465	−0.11203
0.74	−1.90915	0.02504	0.86506	4.72190	0.29309	6.25549	0.26934	−0.12674
0.76	−1.72272	0.02994	0.84712	4.65355	0.34170	5.98304	0.30734	−0.14227
0.78	−1.54554	0.03552	0.82782	4.58283	0.39595	5.71981	0.34902	−0.15861
0.80	−1.37672	0.04186	0.80704	4.50922	0.45650	5.46432	0.39486	−0.17576
0.82	−1.21545	0.04906	0.78463	4.43203	0.52418	5.21508	0.44552	−0.19373
0.84	−1.06097	0.05725	0.76036	4.35043	0.60010	4.97049	0.50187	−0.21254
0.86	−0.91263	0.06658	0.73394	4.26329	0.68574	4.72880	0.56514	−0.23224
0.88	−0.76980	0.07727	0.70491	4.16906	0.78319	4.48793	0.63709	−0.25290
0.90	−0.63192	0.08961	0.67262	4.06548	0.89550	4.24517	0.72040	−0.27461
0.92	−0.49847	0.10407	0.63605	3.94904	1.02744	3.99668	0.81928	−0.29750
0.94	−0.36898	0.12143	0.59347	3.81358	1.18719	3.73613	0.94120	−0.32176
0.96	−0.24301	0.14328	0.54146	3.64643	1.39116	3.45088	1.10146	−0.34766
0.98	−0.12014	0.17412	0.47112	3.41136	1.68360	3.10521	1.34235	−0.37560
1.00	0.00000	0.29010	0.29010	2.58438	2.58438	2.17799	2.17799	−0.40639

TABLA A.15.2 *Factor de compresibilidad de un fluido simple, Z*

T_r \ P_r	0.10	0.20	0.40	0.60	0.80	1.00	1.20	1.40	1.70	2.00	2.50	3.00	5.00	7.00	10.00
0.30	0.0290	0.0579	0.1158	0.1737	0.2315	0.2892	0.3470	0.4047	0.4911	0.5775	0.7213	0.8648	1.4366	2.0048	2.8507
0.40	0.0239	0.0477	0.0953	0.1429	0.1904	0.2379	0.2853	0.3327	0.4036	0.4744	0.5921	0.7095	1.1758	1.6373	2.3211
0.50	0.0207	0.0413	0.0825	0.1236	0.1647	0.2056	0.2465	0.2873	0.3483	0.4092	0.5103	0.6110	1.0094	1.4017	1.9801
0.60	0.0186	0.0371	0.0741	0.1109	0.1476	0.1842	0.2207	0.2571	0.3115	0.3657	0.4554	0.5446	0.8959	1.2398	1.7440
0.70	0.0172	0.0344	0.0687	0.1027	0.1366	0.1703	0.2038	0.2372	0.2869	0.3364	0.4181	0.4991	0.8161	1.1241	1.5729
0.75	0.9165	0.0336	0.0670	0.1001	0.1330	0.1656	0.1981	0.2303	0.2784	0.3260	0.4046	0.4823	0.7854	1.0787	1.5047
0.80	0.9319	0.8539	0.0661	0.0985	0.1307	0.1626	0.1942	0.2255	0.2721	0.3182	0.3942	0.4690	0.7598	1.0400	1.4456
0.85	0.9436	0.8810	0.0661	0.0983	0.1301	0.1614	0.1924	0.2230	0.2684	0.3132	0.3868	0.4591	0.7388	1.0071	1.3943
0.90	0.9528	0.9015	0.7800	0.1006	0.1321	0.1630	0.1935	0.2235	0.2678	0.3114	0.3828	0.4527	0.7220	0.9793	1.3496
0.95	0.9600	0.9174	0.8206	0.6967	0.1410	0.1705	0.1998	0.2288	0.2717	0.3138	0.3827	0.4501	0.7092	0.9561	1.3108
1.00	0.9659	0.9300	0.8509	0.7574	0.6353	0.2901	0.2237	0.2459	0.2839	0.3229	0.3880	0.4522	0.7004	0.9372	1.2772
1.05	0.9707	0.9401	0.8743	0.8002	0.7130	0.6026	0.4437	0.3246	0.3182	0.3452	0.4014	0.4604	0.6956	0.9222	1.2481
1.10	0.9747	0.9485	0.8930	0.8323	0.7649	0.6880	0.5984	0.5003	0.4086	0.3953	0.4277	0.4770	0.6950	0.9110	1.2232
1.15	0.9780	0.9554	0.9081	0.8576	0.8032	0.7443	0.6803	0.6129	0.5227	0.4760	0.4718	0.5042	0.6987	0.9033	1.2021
1.20	0.9808	0.9611	0.9205	0.8779	0.8330	0.7858	0.7363	0.6856	0.6135	0.5605	0.5295	0.5425	0.7069	0.8990	1.1844
1.30	0.9852	0.9702	0.9396	0.9083	0.8764	0.8438	0.8111	0.7784	0.7316	0.6908	0.6467	0.6344	0.7358	0.8998	1.1580
1.40	0.9884	0.9768	0.9534	0.9298	0.9062	0.8827	0.8595	0.8367	0.8043	0.7753	0.7387	0.7202	0.7761	0.9112	1.1419
1.50	0.9909	0.9818	0.9636	0.9456	0.9278	0.9103	0.8933	0.8768	0.8536	0.8328	0.8052	0.7887	0.8200	0.9297	1.1339
1.60	0.9928	0.9856	0.9714	0.9575	0.9439	0.9308	0.9180	0.9059	0.8889	0.8738	0.8537	0.8410	0.8617	0.9518	1.1320
1.80	0.9955	0.9910	0.9823	0.9739	0.9659	0.9583	0.9511	0.9444	0.9353	0.9275	0.9176	0.9118	0.9297	0.9961	1.1391
2.00	0.9972	0.9944	0.9892	0.9842	0.9796	0.9754	0.9715	0.9680	0.9635	0.9599	0.9561	0.9550	0.9772	1.0328	1.1516
2.50	0.9994	0.9989	0.9981	0.9975	0.9971	0.9969	0.9970	0.9973	0.9982	0.9996	1.0031	1.0080	1.0395	1.0866	1.1763
3.00	1.0004	1.0008	1.0018	1.0030	1.0043	1.0057	1.0074	1.0091	1.0121	1.0153	1.0215	1.0284	1.0635	1.1075	1.1848
3.50	1.0008	1.0017	1.0035	1.0055	1.0075	1.0097	1.0120	1.0143	1.0181	1.0221	1.0292	1.0368	1.0723	1.1138	1.1834
4.00	1.0010	1.0021	1.0043	1.0066	1.0090	1.0115	1.0140	1.0166	1.0207	1.0249	1.0323	1.0401	1.0747	1.1136	1.1773
5.00	1.0012	1.0024	1.0048	1.0073	1.0098	1.0124	1.0150	1.0176	1.0217	1.0259	1.0331	1.0405	1.0722	1.1064	1.1611

TABLA A.20 *Masas atómicas y temperaturas de fusión y ebullición de los elementos basados en la masa atómica relativa asignada de $^{12}C = 12$*

Nombre	Símbolo	Número atómico	Masa atómica	Temperatura de fusión, °C	Temperatura de ebullición, °C
Actinio	Ac	89	227.028[a]	1050	3200 ± 300
Aluminio	Al	13	26.9815	660.37	2467
Americio	Am	95	(243)	994 ± 4	2607
Antimonio (estibium)	Sb	51	121.75	630.74	1750
Argón	Ar	18	39.948	−189.2	−185.7
Arsénico	As	33	74.9216	817 (28 atm)	613 (sub)
Astatino	At	85	(210)	302	337
Azufre	S	16	32.06	112.8	444.674
Bario	Ba	56	137.33	725	1640
Berkelio	Bk	97	(247)		
Berilio	Be	4	9.012 18	1278 ± 5	2970 (5 mm)
Bismuto	Bi	83	208.980	271.3	1560 ± 5
Boro	B	5	10.81	2079	2550 (sub)
Bromo	Br	35	79.904	−7.2	58.78
Cadmio	Cd	48	112.41	320.9	765
Calcio	Ca	20	40.08	839 ± 2	1484
Californio	Cf	98	(251)		
Carbón	C	6	12.011	3652 (sub)	t
Cerio	Ce	58	140.12	798 ± 2	3257
Cesio	Cs	55	132.905	28.40 ± 0.01	669.3
Cloro	Cl	17	35.453	−100.98	−34.6
Cromo	Cr	24	51.996	1857 ± 20	2672
Cobalto	Co	27	51.9332	1495	2870
Cobre	Cu	29	63.546	1083.4 ± 0.2	2567
Curio	Cm	96	(247)	1340 ± 40	
Disprosio	Dy	66	162.50	1409	2335
Einstenio	Es	99	(252)		
Erbio	Er	68	167.26	1522	2510
Escandio	Sc	21	44.9559	1539	2832
Estaño	Sn	50	118.71	231.9681	2270
Estroncio	Sr	38	87.62	769	1384
Europio	Eu	63	151.96	822 ± 5	1597
Fermio	Fm	100	(257)		
Flúor	F	9	18.9984	−219.62	−188.14
Fósforo	P	15	30.9738	44.1 (blanco)	280 (blanco)
Francio	Fr	87	(223)	(27)	(677)
Gadolinio	Gd	64	157.25	1311 ± 1	3233

[a] Los valores se aplican a los elementos tal como existen en los materiales de origen terrestre y a ciertos elementos artificiales.
Fuente: *Handbook of Chemistry and Physics*, sexagésima séptima edición, 1986-1987, CRC Press, Boca Raton, Fl, 1986.

TABLA A.20 (Continuación) *Masas atómicas y temperaturas de fusión y ebullición de los elementos basados en la masa atómica relativa asignada de $^{12}C = 12$*

Nombre	Símbolo	Número atómico	Masa atómica	Temperatura de fusión, °C	Temperatura de ebullición, °C
Galio	Ga	31	69.72	29.78	2403
Germanio	Ge	32	72.59	937.4	2830
Hafnio	Hf	72	178.49	2227 ± 20	4602
Helio	He	2	4.002 60	−272.2[26 atm]	−268.934
Hidrógeno	H	1	1.007 94	−259.14	−252.87
Hierro	Fe	26	55.847	1535	2750
Holmio	Ho	67	164.930	1470	2720
Indio	In	49	114.82	156.61	2080
Iridio	Ir	77	192.22	2410	4130
Kriptón	Kr	36	83.80	−156.6	−152.30 ± 0.10
Lantano	La	57	138.906	920 ± 5	3454
Lawrencio	Lr	103	(260)		
Litio	Li	3	6.941	180.54	1342
Lutecio	Lu	71	174.967	1656 ± 5	3315
Magnesio	Mg	12	24.305	648.8 ± 0.5	1090
Manganeso	Mn	25	54.9380	1244 ± 3	1962
Mendelevio	Md	101	(258)		
Mercurio	Hg	80	200.59	−38.87	356.58
Molibdeno	Mo	42	95.94	2617	4612
Neodimio	Nd	60	144.24	1010	3127
Neón	Ne	10	20.1179	−248.67	−246.048
Neptunio	Np	93	237.048	640 ± 1	3902
Niobio	Nb	41	92.9064	2468 ± 10	4742
Níquel	Ni	28	58.69	1453	2732
Nitrógeno	N	7	14.0067	−209.86	−195.8
Nobelio	No	102	(259)		
Oro	Au	79	196.967	1064.434	3080
Osmio	Os	76	190.2	3045 ± 30	5027 ± 100
Oxígeno	O	8	15.9994	−218.4	−182.962
Paladio	Pd	46	106.42	1554	3140
Plata	Ag	47	107.868	961.93	2212
Platino	Pt	78	195.08	1772	3827 ± 100
Plomo	Pb	82	207.2	327.502	1740
Plutonio	Pu	94	(244)	641	3232
Polonio	Po	84	(209)	254	962
Potasio	K	19	39.0983	63.25	759.9

TABLA A.20 (Continuación) *Masas atómicas y temperaturas de fusión y ebullición de los elementos basados en la masa atómica relativa asignada de $^{12}C = 12$*

Nombre	Símbolo	Número atómico	Masa atómica	Temperatura de fusión, °C	Temperatura de ebullición, °C
Praseodimio	Pr	59	140.908	931 ± 4	3212
Prometio	Pm	61	(145)	1080 (aprox.)	2460 (?)
Protoactinio	Pa	91	231.0359	1600	
Radio	Ra	88	226.025	700	1140
Radón	Rn	86	(222)	−71	−61.8
Renio	Re	75	186.207	3180	5627 (est.)
Rodio	Rh	45	102.906	1965 ± 3	3727 ± 100
Rubidio	Rb	37	85.4678	38.89	686
Rutenio	Ru	44	101.07	2310	3900
Samario	Sm	62	150.36	1072 ± 5	1778
Selenio	Se	34	78.96	217	684.9 ± 1.0
Silicio	Si	14	28.0855	1410	2355
Sodio	Na	11	22.9898	97.81 ± 0.03	882.9
Talio	Tl	81	204.383	303.5	1457 ± 10
Tantalio	Ta	73	180.9479	2996	5425 ± 100
Tecnecio	Tc	43	(98)	2172	4877
Telurio	Te	52	127.60	449.5 ± 0.3	989.8 ± 3.8
Terbio	Tb	65	158.925	1360 ± 4	3041
Titanio	Ti	22	47.88	1660 ± 10	3287
Torio	Th	90	232.038	1750	4790 (aprox.)
Tulio	Tm	69	168.934	1545 ± 15	1727
Tungsteno	W	74	183.85	3410 ± 20	5660
Unnihexio	(Unh)	106	(263)		
Unnilcuadio	(Unq)	104	(261)		
Unnilpentio	(Unp)	105	(262)		
Unnilseptio	(Uns)	107	(262)		
Uranio	U	92	238.029	1132 ± 0.8	3818
Vanadio	V	23	50.9415	1890 ± 10	3380
Wolframio (ver tungsteno)					
Xenón	Xe	54	131.29	−111.9	−107.1 ± 3
Yodo	I	53	126.905	113.5	184.35
Yterbio	Yb	70	173.04	824 ± 5	1193
Ytrio	Y	39	88.9059	1523 ± 8	3337
Zinc	Zn	30	65.39	419.58	907
Zirconio	Zr	40	91.224	1852 ± 2	4377

TABLA A.11 *Propiedades termodinámicas del agua (unidades inglesas)*
TABLA A.1.11 *Agua saturada: tabla de temperatura (unidades inglesas)*

		Volumen específico, pies³/libra		Energía interna, Btu/lbm			Entalpía, Btu/lbm			Entropía, Btu/lbm°R		
Temp. °F T	Presión lbf/pulg² P	Líquido saturado v_f	Vapor saturado v_g	Líquido saturado u_f	Evap. u_{fg}	Vapor saturado u_g	Líquido saturado h_f	Evap. h_{fg}	Vapor saturado h_g	Líquido saturado s_f	Evap. s_{fg}	Vapor saturado s_g
32	0.08867	0.016022	3301.9	0.00	1021.2	1021.2	0.00	1075.4	1075.4	0.00000	2.1869	2.1869
35	0.09993	0.016021	2947.5	2.99	1019.2	1022.2	2.99	1073.7	1076.7	0.00607	2.1703	2.1764
40	0.12167	0.016020	2445.1	8.01	1015.8	1023.8	8.01	1070.9	1078.9	0.01617	2.1430	2.1591
45	0.14750	0.016021	2037.0	13.03	1012.5	1025.5	13.03	1068.1	1081.1	0.02617	2.1161	2.1423
50	0.17805	0.016024	1704.0	18.05	1009.1	1027.2	18.05	1065.2	1083.3	0.03606	2.0898	2.1259
60	0.2563	0.016034	1206.7	28.08	1002.4	1030.4	28.08	1059.6	1087.7	0.05554	2.0388	2.0943
70	0.3632	0.016051	867.60	38.09	995.6	1033.7	38.09	1054.0	1092.0	0.07462	1.9896	2.0642
80	0.5074	0.016072	632.69	48.08	988.9	1037.0	48.08	1048.3	1096.4	0.09331	1.9423	2.0356
90	0.6989	0.016099	467.60	58.06	982.2	1040.2	58.06	1042.7	1100.7	0.11163	1.8966	2.0083
100	0.9504	0.016130	349.98	68.04	975.4	1043.5	68.04	1037.0	1105.0	0.12962	1.8526	1.9822
110	1.2765	0.016166	265.07	78.01	968.7	1046.7	78.01	1031.3	1109.3	0.14728	1.8101	1.9574
120	1.6947	0.016205	203.03	87.99	961.9	1049.9	87.99	1025.5	1113.5	0.16464	1.7690	1.9336
130	2.2254	0.016247	157.16	97.96	955.1	1053.0	97.97	1019.8	1117.7	0.18171	1.7292	1.9109
140	2.892	0.016293	122.87	107.95	948.2	1056.2	107.96	1014.0	1121.9	0.19850	1.6907	1.8892
150	3.722	0.016343	96.977	117.94	941.3	1059.3	117.95	1008.1	1126.1	0.21502	1.6533	1.8683
160	4.745	0.016395	77.224	127.94	934.4	1062.3	127.95	1002.2	1130.1	0.23129	1.6171	1.8484
170	5.997	0.016450	62.015	137.94	927.4	1065.4	137.96	996.2	1134.2	0.24731	1.5819	1.8292
180	7.515	0.016509	50.199	147.96	920.4	1068.3	147.98	990.2	1138.2	0.26309	1.5478	1.8109
190	9.344	0.016570	40.942	157.99	913.3	1071.3	158.02	984.1	1142.1	0.27865	1.5146	1.7932
200	11.530	0.016634	33.631	168.03	906.2	1074.2	168.07	977.9	1145.9	0.29399	1.4822	1.7762
210	14.126	0.016702	27.813	178.09	898.9	1077.0	178.13	971.6	1149.7	0.30912	1.4507	1.7599
212	14.699	0.016715	26.797	180.10	897.5	1077.6	180.15	970.3	1150.5	0.31212	1.4445	1.7567
220	17.189	0.016772	23.149	188.16	891.7	1079.8	188.21	965.3	1153.5	0.32404	1.4201	1.7441
230	20.780	0.016845	19.385	198.25	884.3	1082.6	198.31	958.8	1157.1	0.33878	1.3901	1.7289
240	24.968	0.016922	16.326	208.36	876.9	1085.3	208.43	952.3	1160.7	0.35333	1.3609	1.7142
250	29.823	0.017001	13.825	218.48	869.4	1087.9	218.58	945.6	1164.2	0.36771	1.3324	1.7001
260	35.422	0.017084	11.767	228.64	861.8	1090.5	228.75	938.8	1167.6	0.38191	1.3044	1.6864
270	41.848	0.017170	10.065	238.81	854.1	1092.9	238.95	932.0	1170.9	0.39596	1.2771	1.6731
280	49.189	0.017259	8.650	249.02	846.4	1095.4	249.17	924.9	1174.1	0.40985	1.2504	1.6602
290	57.535	0.017352	7.466	259.25	838.5	1097.7	259.43	917.8	1177.2	0.42359	1.2241	1.6477
300	66.985	0.017448	6.471	269.51	830.5	1100.0	269.73	910.4	1180.2	0.43719	1.1984	1.6356
310	77.641	0.017548	5.631	279.80	822.3	1102.1	280.06	903.0	1183.0	0.45065	1.1731	1.6238
320	89.609	0.017652	4.919	290.13	814.1	1104.2	290.43	895.3	1185.8	0.46399	1.1483	1.6122
330	103.00	0.017760	4.312	300.50	805.7	1106.2	300.84	887.5	1188.4	0.47720	1.1238	1.6010
340	117.94	0.017871	3.792	310.90	797.1	1108.0	311.29	879.5	1190.8	0.49030	1.0997	1.5900

Oxígeno Sobrecalentado

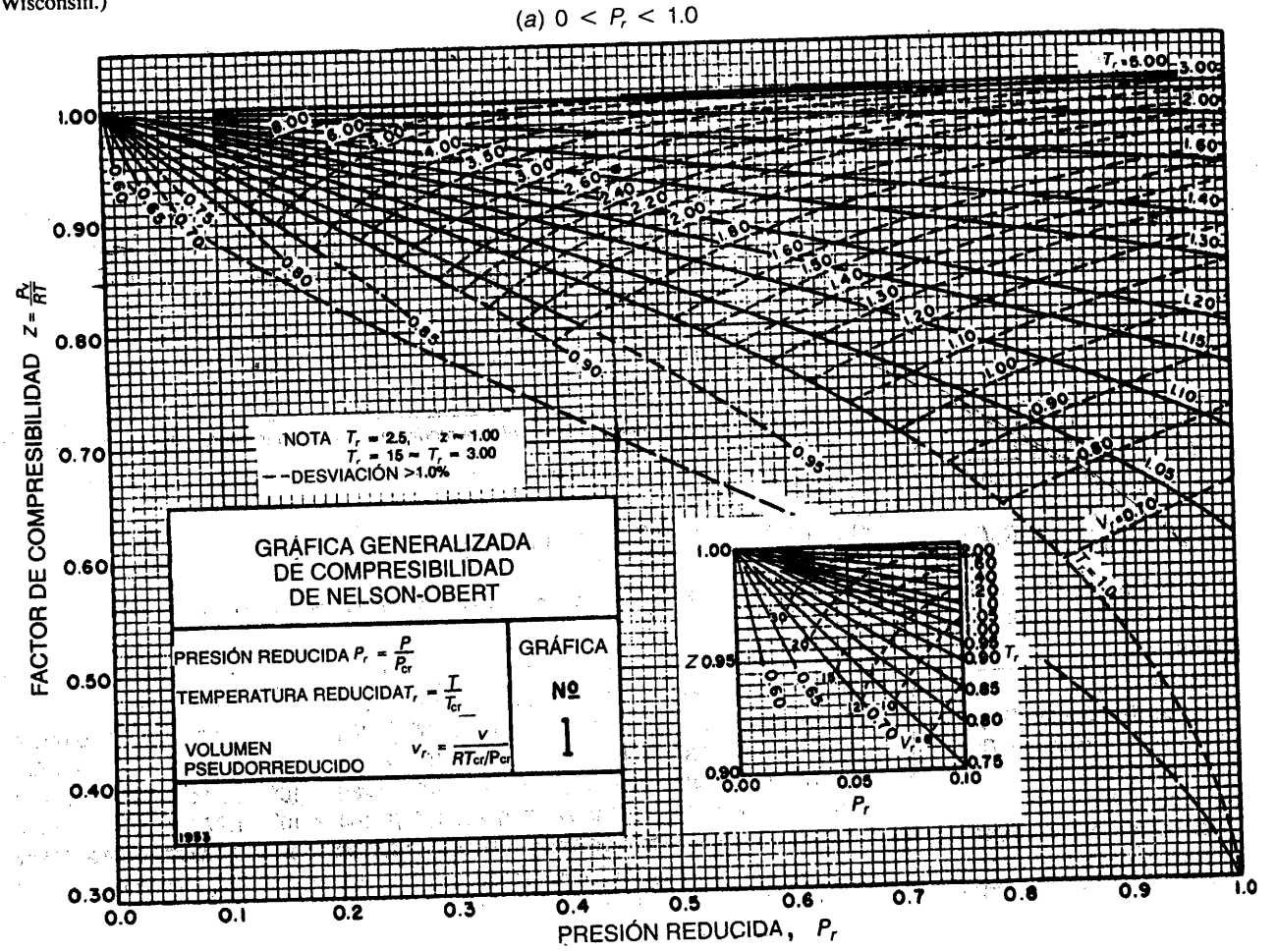
Temp (K)	v (m^3/kg)	h (kJ/kg)	s (kJ/kgK)	v (m^3/kg)	h (kJ/kg)	s (kJ/kgK)	v (m^3/kg)	h (kJ/kg)	s (kJ/kgK)
		0.10 MPa			0.20 MPa			0.50 MPa	
100	0.253503	88.828	5.4016	0.123394	86.864	5.2083			
125	0.320717	112.214	5.6107	0.158268	110.988	5.4241	0.060674	107.093	5.1650
150	0.386914	135.301	5.7787	0.192016	134.440	5.5947	0.075039	131.788	5.3448
175	0.452645	158.255	5.9202	0.225276	157.609	5.7376	0.088842	155.643	5.4919
200	0.518127	181.145	6.0427	0.258282	180.638	5.8609	0.102371	179.105	5.6175
225	0.583465	204.007	6.1502	0.291140	203.596	5.9688	0.115746	202.359	5.7268
250	0.648711	226.869	6.2468	0.323906	226.529	6.0657	0.129025	225.506	5.8246
275	0.713895	249.769	6.3369	0.356610	249.483	6.1560	0.142242	248.621	5.9156
300	0.779036	272.720	6.4140	0.389271	272.475	6.2332	0.155415	271.740	5.9932
		1.00 MPa			2.00 MPa			4.00 MPa	
125	0.027869	99.653	4.9431						
150	0.035976	127.112	5.1433	0.016270	116.476	4.9130	0.005526	81.481	4.5475
175	0.043341	152.269	5.2986	0.020544	145.112	5.0899	0.009029	128.618	4.8414
200	0.050394	176.508	5.4283	0.024395	171.150	5.2293	0.011376	159.715	5.0080
225	0.057282	200.280	5.5401	0.028051	196.052	5.3464	0.013444	187.333	5.1380
250	0.064068	223.795	5.6394	0.031597	220.348	5.4491	0.015378	213.374	5.2480
275	0.070790	247.185	5.7314	0.035073	244.309	5.5433	0.017233	238.560	5.3469
300	0.077467	270.516	5.8098	0.038502	268.076	5.6263	0.019039	263.234	5.4300
		6.00 MPa			8.00 MPa			10.00 MPa	
175	0.005051	107.496	4.6431	0.003002	79.513	4.4384	0.002020	52.661	4.2573
200	0.007027	147.232	4.8565	0.004864	133.760	4.7308	0.003603	119.767	4.6189
225	0.008589	178.304	5.0029	0.006181	169.069	4.8973	0.004757	159.686	4.8072
250	0.009991	206.340	5.1214	0.007316	199.317	5.0251	0.005730	192.401	4.9450
275	0.011306	232.848	5.2253	0.008360	227.219	5.1344	0.006606	221.685	5.0572
300	0.012570	258.464	5.3116	0.009351	253.797	5.2240	0.007432	249.262	5.1533
		20.00 MPa							
175	0.001343	24.551	4.0086						
200	0.001727	75.318	4.2798						
225	0.002236	122.595	4.5024						
250	0.002755	163.109	4.6739						
275	0.003241	198.021	4.8069						
300	0.003700	229.655	4.9174						

Oxígeno Saturado

		Volumen específico (m^3/kg)			Entalpia (kJ/kg)			Entropía (kJ/kg.K)		
Temp (K)	P (MPa)	v_f	v_{fg}	v_g	h_f	h_{fg}	h_g	s_f	s_{fg}	s_g
54.3507	0.00015	0.000765	92.9658	92.9666	-193.432	242.553	49.121	2.0938	4.4514	6.5452
60	0.00073	0.000780	21.3461	21.3469	-184.029	238.265	54.236	2.2585	3.9686	6.2271
70	0.00623	0.000808	2.9085	2.9093	-167.372	230.527	63.155	2.5151	3.2936	5.8087
80	0.03006	0.000840	0.68104	0.68188	-150.646	222.289	71.643	2.7381	2.7779	5.5161
90	0.09943	0.000876	0.22649	0.22736	-133.758	213.070	79.312	2.9364	2.3663	5.3027
100	0.25425	0.000917	0.094645	0.095562	-116.557	202.291	85.734	3.1161	2.0222	5.1383
110	0.54339	0.000966	0.045855	0.046821	-98.829	189.320	90.491	3.2823	1.7210	5.0033
120	1.0215	0.001027	0.024336	0.025363	-80.219	173.310	93.091	3.4401	1.4445	4.8846
130	1.7478	0.001108	0.013488	0.014596	-60.6093	152.887	92.794	3.5948	1.1766	4.7714
140	2.7866	0.001230	0.007339	0.008569	-37.045	125.051	88.006	3.7567	0.8935	4.6502
150	4.2190	0.001480	0.003180	0.004660	-7.038	79.459	72.421	3.9498	0.5301	4.4799
154.576	5.0427	0.002293	0.000000	0.002293	32.257	0.000	32.257	4.1977	0.0000	4.1977

FIGURA A-30*a*

Gráfica generalizada de compresibilidad de Nelson-Obert-*bajas presiones*. (Utilizadas con permiso del Dr. Edward E. Obert, University of Wisconsin.)



ASME TEST FORM
CALCULATION SHEET — FOR ABBREVIATED EFFICIENCY TEST

Revised September, 1965

OWNER OF PLANT	TEST NO.	BOILER NO.	DATE

30 HEAT OUTPUT IN BOILER BLOW-DOWN WATER = LB OF WATER BLOW-DOWN PER HR × [(ITEM 15 ..... − ITEM 17 .....) / 1000] = ... kB/hr

24 *If impractical to weigh refuse, this item can be estimated as follows*

DRY REFUSE PER LB OF AS FIRED FUEL = (% ASH IN AS FIRED COAL) / (100 − % COMB. IN REFUSE SAMPLE)

CARBON BURNED PER LB AS FIRED FUEL = (ITEM 43 ...../100) − [(ITEM 22 ..... × ITEM 23 .....)/14,500] = ...

NOTE: IF FLUE DUST & ASH PIT REFUSE DIFFER MATERIALLY IN COMBUSTIBLE CONTENT, THEY SHOULD BE ESTIMATED SEPARATELY. SEE SECTION 7, COMPUTATIONS.

25 DRY GAS PER LB AS FIRED FUEL BURNED = $\frac{11CO_2 + 8O_2 + 7(N_2 + CO)}{3(CO_2 + CO)}$ × (LB CARBON BURNED PER LB AS FIRED FUEL + $\frac{3}{8}$ S)

$$= \frac{11 \times \text{ITEM 32} + 8 \times \text{ITEM 33} + 7(\text{ITEM 35} + \text{ITEM 34})}{3 \times (\text{ITEM 32} + \text{ITEM 34})} \times \left[\text{ITEM 24} + \frac{\text{ITEM 47}}{267}\right] = ...$$

36 EXCESS AIR † = $100 \times \frac{O_2 - \frac{CO}{2}}{.2682N_2 - (O_2 - \frac{CO}{2})} = 100 \times \frac{\text{ITEM 33} - \frac{\text{ITEM 34}}{2}}{.2682\,(\text{ITEM 35}) - (\text{ITEM 33} - \frac{\text{ITEM 34}}{2})} =$ .....

	HEAT LOSS EFFICIENCY	Btu/lb AS FIRED FUEL	$\frac{\text{LOSS}}{\text{HHV}} \times \frac{}{100}$ =	LOSS %
65	HEAT LOSS DUE TO DRY GAS = LB DRY GAS PER LB AS FIRED FUEL × C_p × ($t_{lvg} - t_{air}$) = ITEM 25 ..... × 0.24 × (ITEM 13) − (ITEM 11) = ...	.....	$\frac{65}{41} \times 100 =$	.....
66	HEAT LOSS DUE TO MOISTURE IN FUEL = LB H_2O PER LB AS FIRED FUEL × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = ITEM 37 ..... / 100 × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) − (ENTHALPY OF LIQUID AT T ITEM 11)] = ...	.....	$\frac{66}{41} \times 100 =$	.....
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2 = $9H_2$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = 9 × ITEM 44 ..... / 100 × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) − (ENTHALPY OF LIQUID AT T ITEM 11)] = ...	.....	$\frac{67}{41} \times 100 =$	.....
68	HEAT LOSS DUE TO COMBUSTIBLE IN REFUSE = ITEM 22 ..... × ITEM 23 ..... = ...	.....	$\frac{68}{41} \times 100 =$	.....
69	HEAT LOSS DUE TO RADIATION* = TOTAL BTU RADIATION LOSS PER HR / (LB AS FIRED FUEL − ITEM 28 .....)	.....	$\frac{69}{41} \times 100 =$	.....
70	UNMEASURED LOSSES **	.....	$\frac{70}{41} \times 100 =$	.....
71	TOTAL	.....	.....	.....
72	EFFICIENCY = (100 − ITEM 71)	.....	.....	.....

† For rigorous determination of excess air see Appendix 9.2 – PTC 4.1-1964

*If losses are not measured, use ABMA Standard Radiation Loss Chart, Fig. 8, PTC 4.1-1964

** Unmeasured losses listed in PTC 4.1 but not tabulated above may by provided for by assigning a mutually agreed upon value for Item 70.

Printed in U.S.A. (10/74)

This Test Form (C-37) may be obtained from ASME, 345 E. 47 St., New York, N.Y. 10017

SUMMARY SHEET

ASME TEST FORM FOR ABBREVIATED EFFICIENCY TEST

PTC 4.1-a (1964)

	TEST NO.	BOILER NO.	DATE
OWNER OF PLANT	LOCATION		
TEST CONDUCTED BY	OBJECTIVE OF TEST		DURATION
BOILER MAKE & TYPE		RATED CAPACITY	
STOKER TYPE & SIZE			
PULVERIZER, TYPE & SIZE		BURNER, TYPE & SIZE	
FUEL USED	MINE	COUNTY	STATE / SIZE AS FIRED

PRESSURES & TEMPERATURES

1	STEAM PRESSURE IN BOILER DRUM	psia	
2	STEAM PRESSURE AT S. H. OUTLET	psia	
3	STEAM PRESSURE AT R. H. INLET	psia	
4	STEAM PRESSURE AT R. H. OUTLET	psia	
5	STEAM TEMPERATURE AT S. H. OUTLET	F	
6	STEAM TEMPERATURE AT R H INLET	F	
7	STEAM TEMPERATURE AT R.H. OUTLET	F	
8	WATER TEMP. ENTERING (ECON) (BOILER)	F	
9	STEAM QUALITY % MOISTURE OR P. P. M.		
10	AIR TEMP. AROUND BOILER (AMBIENT)	F	
11	TEMP AIR FOR COMBUSTION (This is Reference Temperature) †	F	
12	TEMPERATURE OF FUEL	F	
13	GAS TEMP. LEAVING (Boiler) (Econ.) (Air Htr.)	F	
14	GAS TEMP. ENTERING AH (If conditions to be corrected to guarantee)	F	

UNIT QUANTITIES

15	ENTHALPY OF SAT. LIQUID (TOTAL HEAT)	Btu/lb	
16	ENTHALPY OF (SATURATED) (SUPERHEATED) STM.	Btu/lb	
17	ENTHALPY OF SAT. FEED TO (BOILER) (ECON.)	Btu/lb	
18	ENTHALPY OF REHEATED STEAM R.H. INLET	Btu/lb	
19	ENTHALPY OF REHEATED STEAM R. H. OUTLET	Btu/lb	
20	HEAT ABS./LB OF STEAM (ITEM 16 – ITEM 17)	Btu/lb	
21	HEAT ABS./LB R.H. STEAM (ITEM 19 – ITEM 18)	Btu/lb	
22	DRY REFUSE (ASH PIT + FLY ASH) PER LB AS FIRED FUEL	lb/lb	
23	Btu PER LB IN REFUSE (WEIGHTED AVERAGE)	Btu/lb	
24	CARBON BURNED PER LB AS FIRED FUEL	lb/lb	
25	DRY GAS PER LB AS FIRED FUEL BURNED	lb/lb	

HOURLY QUANTITIES

26	ACTUAL WATER EVAPORATED	lb/hr	
27	REHEAT STEAM FLOW	lb/hr	
28	RATE OF FUEL FIRING (AS FIRED wt)	lb/hr	
29	TOTAL HEAT INPUT $\frac{(\text{Item 28} \times \text{Item 41})}{1000}$	kB/hr	
30	HEAT OUTPUT IN BLOW-DOWN WATER	kB/hr	
31	TOTAL HEAT OUTPUT $\frac{(\text{Item 26} \times \text{Item 20}) + (\text{Item 27} \times \text{Item 21}) + \text{Item 30}}{1000}$	kB/hr	

FLUE GAS ANAL. (BOILER) (ECON) (AIR HTR) OUTLET

32	CO_2	% VOL	
33	O_2	% VOL	
34	CO	% VOL	
35	N_2 (BY DIFFERENCE)	% VOL	
36	EXCESS AIR	%	

FUEL DATA

	COAL AS FIRED PROX. ANALYSIS	% wt			OIL		
37	MOISTURE			51	FLASH POINT F*		
38	VOL MATTER			52	Sp. Gravity Deg. API*		
39	FIXED CARBON			53	VISCOSITY AT SSU* BURNER SSF		
40	ASH			44	TOTAL HYDROGEN % wt		
	TOTAL			41	Btu per lb		
41	Btu per lb AS FIRED						
42	ASH SOFT TEMP.* ASTM METHOD				GAS	% VOL	
	COAL OR OIL AS FIRED ULTIMATE ANALYSIS			54	CO		
43	CARBON			55	CH_4 METHANE		
44	HYDROGEN			56	C_2H_2 ACETYLENE		
45	OXYGEN			57	C_2H_4 ETHYLENE		
46	NITROGEN			58	C_2H_6 ETHANE		
47	SULPHUR			59	H_2S		
40	ASH			60	CO_2		
37	MOISTURE			61	H_2 HYDROGEN		
	TOTAL				TOTAL		
	COAL PULVERIZATION				TOTAL HYDROGEN % wt		
48	GRINDABILITY INDEX*			62	DENSITY 68 F ATM. PRESS.		
49	FINENESS % THRU 50 M*			63	Btu PER CU FT		
50	FINENESS % THRU 200 M*			41	Btu PER LB		
64	INPUT-OUTPUT EFFICIENCY OF UNIT %		$\frac{\text{ITEM 31} \times 100}{\text{ITEM 29}}$				

	HEAT LOSS EFFICIENCY	Btu/lb A. F. FUEL	% of A. F. FUEL
65	HEAT LOSS DUE TO DRY GAS		
66	HEAT LOSS DUE TO MOISTURE IN FUEL		
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2		
68	HEAT LOSS DUE TO COMBUST. IN REFUSE		
69	HEAT LOSS DUE TO RADIATION		
70	UNMEASURED LOSSES		
71	TOTAL		
72	EFFICIENCY = (100 – Item 71)		

* Not Required for Efficiency Testing

† For Point of Measurement See Par. 7.2.8.1-PTC 4.1-1964

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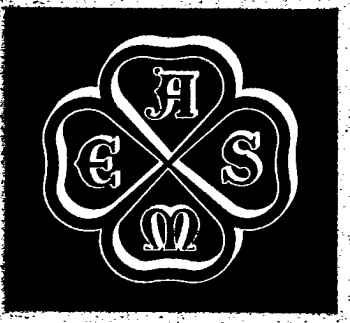
PTC 4.1 - 1964
REAPPROVED '79

Steam Generating Units



POWER TEST CODES

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center
345 East 47th Street New York, N.Y. 10017

Steam Generating Units

POWER TEST CODES

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FOREWORD

THE Test Code for Stationary Steam-Generating Units was one of the group of ten forming the 1915 Edition of the ASME Power Test Codes. A revision of these codes was begun in 1918 and the Test Code for Stationary Steam-Generating Units was reissued in revised form in October, 1926. Further revisions were issued in February, 1930 and January, 1936.

In October, 1936 the standing Power Test Codes Committee requested PTC Committee No. 4 to consider a revision of the Code to provide for heat balance tests on large steam generating units. In rewriting the Code advantage was taken of the experience of the several companies in the utility field which had developed test methods for the large modern units including the necessary auxiliary equipment directly involved in the operation of the units. At the same time the needs of the small installations were not overlooked. At the November 30, 1945 meeting of the standing Power Test Codes Committee, this revision was approved and on May 23, 1946 the Code was approved and adopted by the Council.

In view of the continuously increasing size and complexity of steam generating units, it was obvious that changes were required in the 1946 Edition of the Test Code. In May, 1958 the technical committee was reorganized to prepare this revision. The completely revised Code, the Test Code for Steam Generating Units, was approved by the Power Test Codes Committee on March 20, 1964. It was further approved and adopted by the Council as a standard practice of the Society by action of the Board on Codes and Standards on June 24, 1964.

December, 1964

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Frank C. Lisevick, Supervisor – Equipment Test, Research and Development Department, Combustion Engineering, Inc., Prospect Hill Road, Windsor, Connecticut

Robert A. Lorenzini, Vice-President, Equipment Division, Foster Wheeler Corporation, 110 South Orange Avenue, Livingston, New Jersey

John F. McLaughlin, Jr., Manager, Production Engineering, Power Production Division, Union Electric Company of Missouri, 315 North 12th Boulevard, St. Louis 1, Missouri

Silas L. Morse, Assistant Manager, Field Engineering, The Babcock & Wilcox Company, 20 South Van Buren Avenue, Barberton, Ohio

Henry D. Mumper, Engineering Specialist, Engineering Department, Combustion Engineering, Inc., New York, New York (deceased October 9, 1959)

Richard H. Pechstein, Head, Steam Generation Section, Mechanical Engineering Division, American Electric Power Service Corporation, Two Broadway, New York 8, New York

Herbert C. Schweikart, Chief Mechanical Engineer, Mechanical Engineering Department, Gilbert Associates, Inc., 525 Lancaster Avenue, Reading, Pennsylvania

Lawson E. Stewart, Sales Representative, International Business Machines Corporation, 2330 St. Paul Street, Baltimore, Maryland, 21218

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ASME POWER TEST CODES
Test Code for Steam Generating Units

CONTENTS

SECTION 0, INTRODUCTION

0.1 This Code contains instructions for testing steam generating units. These units are defined as combinations of apparatus for liberating and recovering heat, together with apparatus for transferring to a working fluid the heat thus made available. For the purpose of this Code, such a unit may include the boiler, furnace, superheater, reheater, economizer, air heater, and fuel-burning equipment. The economizer and air heater are not considered a part of the unit when the heat absorbed by them is not returned to the unit. It is not the intent of these testing procedures to obtain data for establishing design criteria of individual parts of the over-all steam generator. Code Supplements PTC 4.2 and PTC 4.3 cover testing of pulverizers and air heaters, respectively.

0.2 It is intended that in using this Code a detailed examination will be made of the Code on General Instructions PTC 1 and all other Codes herein referred to before starting preparations for the tests. Such study is for the purpose of assuring an orderly and thorough testing procedure since it provides the user with an over-all understanding of the ASME Power Test Codes requirements and enables him to understand readily the interrelationship of the various Codes. Care should be exercised to obtain and use the latest revisions of the Codes.

0.3 While Section 2 of this Code is concerned with symbols and their descriptions applying specifically to testing of steam generating units, the user is referred to the Code on Definitions and Values PTC 2 for a more complete discussion of the items which will be encountered.

0.4 The Supplements on Instruments and Apparatus PTC 19 referred to herein should be studied thoroughly because the value of the test results depends on the selection and application of the instruments, their calibration and the accuracy of the readings.

0.4.1 Other items of vital importance to the value of the test are the proper determination of the high-heat value and other properties of the fuel used. The appropriate Code for the type of fuel burned and ASTM Standard Method pertaining to Heat of Combustion should be followed carefully.

0.5 This Code is intended as a guide for the conduct of all steam generator tests, but it could not possibly detail a test applicable to every variation in the design of steam generators. In every case a competent engineer must study the particular unit and its relation with the rest of the cycle and develop test procedures which are in agreement with the general accuracy and intention of this Code. Examples of the design variations in operation at the time of preparation of this Code are subcritical and supercritical once-through units and dual-cycle steam generators. Such units were considered as the Code was being prepared and it is believed that the provisions herein can be applied to the testing of such steam generators.

0.6 The general instructions contained in this Code shall also apply to the testing of high temperature water heaters, except that efficiency determination shall be by heat loss method only, as described in Section 5. The input-output method is not acceptable because of potentially large inaccuracies introduced by the presence of indeterminant quantities of steam in the output and by the small temperature measurement errors in a large volume flow output.

Test capacity or output shall be determined from measured heat input and efficiency, or by direct measurement of heat output if a high degree of accuracy is not required.

0.7 The testing of nuclear and combined-cycle steam generators were not included because their development at the time of revising this Code was such that specific recommendations could not be made.

0.8 Advanced instrument systems, such as those using electronic devices or mass flow techniques, may, by mutual agreement, be used as alternates to the mandatory Code instrument requirements, provided that the application of such instruments has demonstrated accuracy equivalent to that required by this Code.

SECTION 1, OBJECT AND SCOPE

1.01 The purpose of this Code is to establish procedures for conducting performance tests to determine:

1.01.1 Efficiency

1.01.2 Capacity

1.01.3 Other related operating characteristics such as steam temperature and control range, exit gas temperature, draft loss, steam – water – and air – pressure drops, solids in steam and air leakage.

1.02 A determination of any or all of the performance items specified above may be necessary for other purposes such as:

1.02.1 Checking the actual performance against guarantee.

1.02.2 Comparing these items with a standard of operation.

1.02.3 Comparing different conditions or methods of operation.

1.02.4 Determining the performance of different parts of the steam generating unit.

1.02.5 Comparing performance when firing different fuels.

1.02.6 Determining the effects of changes to equipment.

1.03 The rules and instructions given in this Code apply to the equipment defined in the introduction. Testing of auxiliary apparatus shall be governed by the Power Test Code applying specifically to the auxiliary in question.

1.04 Instructions are given for two acceptable methods of testing steam generators to determine efficiency. One method is the direct measurement of input and output, hereinafter referred to as the input-output method. The other method is the direct measurement of heat losses and is hereinafter referred to as the heat loss method. The method followed in conducting the tests shall be clearly defined in the report.

1.04.1 The input-output method requires the accurate measurement of the quantity and high-heat value of the fuel, heat credits and the heat absorbed by the working fluid or fluids.

1.04.2 The heat loss method requires the determination of losses, heat credits and ultimate analysis and high-heat value of the fuel. To establish the capacity at which the losses occur it is necessary to measure either the input or output.

1.04.3 Throughout this Code, input is defined as the chemical heat in the fuel(high-heat value of the fuel as determined from laboratory analysis) plus heat credits added to the working fluid or fluids, air, gas and other fluid circuits which cross the envelope boundary as shown in Fig. 1.* The envelope boundary encompasses the equipment to be included in the designation "steam generating unit." Heat input and output that cross the envelope boundary are involved in the efficiency calculations. Apparatus is outside the envelope boundary when it requires an outside source of heat or where the heat exchanged is not returned to the steam generating unit.

1.04.4 The output is defined as the heat absorbed by the working fluid or fluids.

1.04.5 Heat credits are defined as those amounts of heat added to the envelope of the steam generator unit other than the chemical heat in the fuel "as fired". These credits include quantities such as sensible heat (function of specific heat and the measured temperature) in the fuel, in the entering air and in the atomizing steam, and heat from power conversion in pulverizer, circulating pump, primary air fan and recirculating fan.

1.04.6 For a better understanding of the relationships between input, output, credits and losses, refer to Fig. 2.*

1.05 Capacity of steam generators is defined as actual evaporation in pounds of steam per hour delivered or Btu per hour absorbed by the working fluid or fluids. Capacity of hot water heaters is defined as the heat absorbed by water and the heat of any steam that may be generated (Btu per hour).

1.06 The efficiency of steam generating equipment determined within the scope of this Code is the gross efficiency and is defined as the ratio of heat absorbed by the working fluid or fluids to the heat input as defined in Par. 1.04.3. This definition disregards the equivalent heat in the power

*Note: Figs. 1 and 2 are available in pad form through the ASME Order Department.

required by the auxiliary apparatus external to the envelope (See Fig. 1).

1.06.1 Efficiency for the two methods is expressed by the following equations:

Input-Output Method –

$$\text{Efficiency (per cent)} = \frac{\text{Output}}{\text{Input}}$$

$$= \frac{\text{Heat absorbed by working fluid or fluids}}{\text{Heat in fuel + heat credits}} \times 100$$

For derivation see Par. 7.2

Heat Loss Method –

$$\text{Efficiency (per cent)} = 100 - \left(\frac{\text{Heat Losses}}{\text{Heat in fuel + Heat Credits}} \times 100\right)$$

For derivation see Par 7.3.

1.07 For conducting an abbreviated efficiency test that considers only the major losses, and only the chemical heat in the fuel as input, the data and calculation procedures in the ASME Test Report for Simplified Efficiency Test may be used. (Note: These forms are available in pad form through the ASME Order Department.)

The use of abbreviated test procedures are not encouraged, but it is recognized that on routine testing of all sizes of steam generators and on acceptance testing of small heating and industrial steam generators that a simplified test is the only practical approach. Although the abbreviated test procedure ignores the minor losses and heat credits, the test procedures for obtaining the major items will be the same as specified in PTC 4.1, Test Code for Steam Generating Units and therefore the contents of this Code should be read and understood prior to running a simplified efficiency test. Where heat losses are to be adjusted to compensate for variations in fuel, or changes in inlet air temperature, as would be done in verifying an efficiency guarantee, the procedure given in Section 7, Corrections to Standard or Guarantee Conditions of the Code should be followed.

1.08 The adjustment of test results to include the effect of equivalent heat in auxiliary power to determine "net efficiency" is not a requirement of the Code. If net efficiency is to be determined, it shall be by the method given in Par. 6.2.

1.09 Both the heat loss and the input-output methods of this Code apply to steam generating units operating with either solid, liquid or gaseous fuels.

1.09.1 This Code will apply only when tests are run using a single fuel.

1.09.2 Where test have to be made using a combination of fuels, it will be necessary to establish test procedures and calculations based on the guiding principles and general intent of this Code. For assistance in approaching this problem reference is suggested to Volume 78, Transactions ASME, August, 1956 "Combustion Calculations for Multiple Fuels."

1.10 The determination of data of a research nature or other special data is not covered by this Code.

1.11 It is recommended that a report be prepared for each test, either the abbreviated or complete test, giving complete details of the conditions under which the test has been made including a record of test procedures and all data in form suitable for demonstrating that the objectives of the test have been attained.

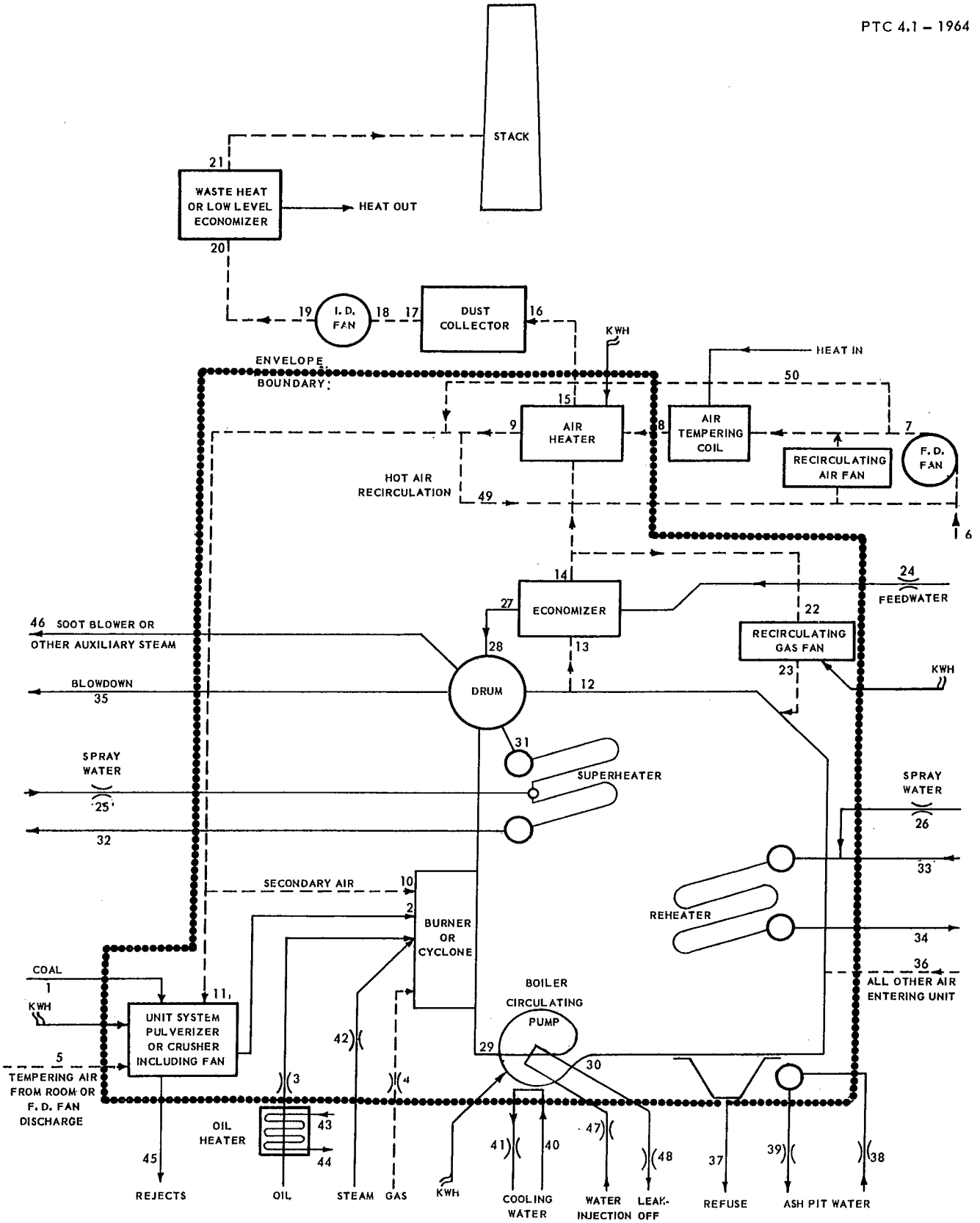
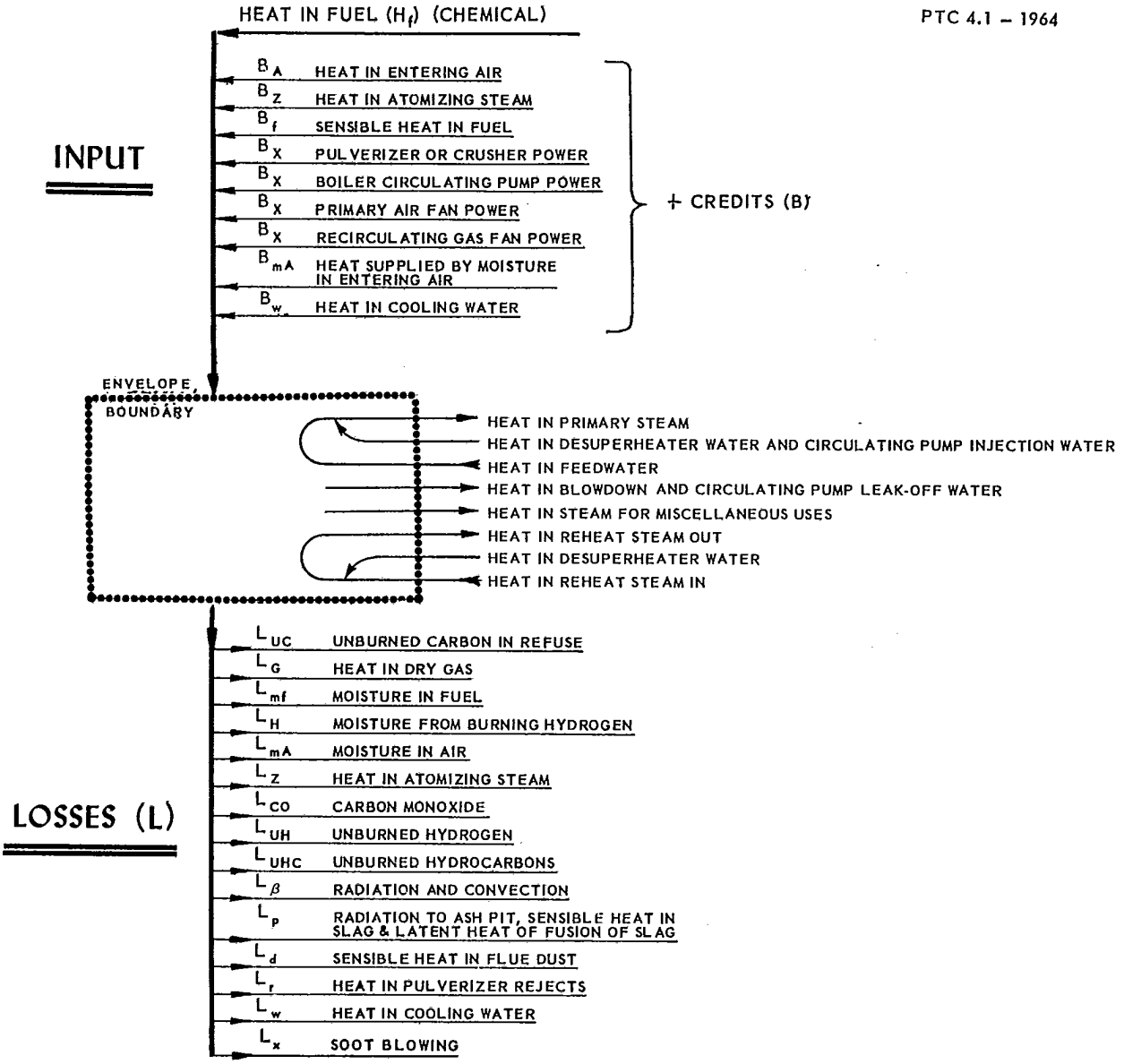


FIG 1 STEAM GENERATING UNIT DIAGRAM



$$\text{OUTPUT} = \text{INPUT} - \text{LOSSES}$$

$$\text{DEFINITION: EFFICIENCY (PERCENT)} = \eta_g\,(\%) = \frac{\text{OUTPUT}}{\text{INPUT}} \times 100 = \frac{\text{INPUT} - L}{H_f + B} \times 100$$

$$\text{HEAT BALANCE: } H_f + B = \text{OUTPUT} + L \quad \text{OR} \quad \eta_g\,(\%) = \left[1 - \frac{L}{H_f + B}\right] \times 100$$

FIG. 2 HEAT BALANCE OF STEAM GENERATOR

ASME TEST FORM FOR ABBREVIATED EFFICIENCY TEST

SUMMARY SHEET

PTC 4.1-a (1964)

	TEST NO.	BOILER NO.	DATE
OWNER OF PLANT	LOCATION		
TEST CONDUCTED BY	OBJECTIVE OF TEST		DURATION
BOILER, MAKE & TYPE		RATED CAPACITY	
STOKER, TYPE & SIZE			
PULVERIZER, TYPE & SIZE		BURNER, TYPE & SIZE	
FUEL USED	MINE	COUNTY	STATE	SIZE AS FIRED

PRESSURES & TEMPERATURES

1	STEAM PRESSURE IN BOILER DRUM	psia	
2	STEAM PRESSURE AT S. H. OUTLET	psia	
3	STEAM PRESSURE AT R. H. INLET	psia	
4	STEAM PRESSURE AT R. H. OUTLET	psia	
5	STEAM TEMPERATURE AT S. H. OUTLET	F	
6	STEAM TEMPERATURE AT R H INLET	F	
7	STEAM TEMPERATURE AT R. H. OUTLET	F	
8	WATER TEMP. ENTERING (ECON.) (BOILER)	F	
9	STEAM QUALITY % MOISTURE OR P. P. M.		
10	AIR TEMP. AROUND BOILER (AMBIENT)	F	
11	TEMP AIR FOR COMBUSTION (This is Reference Temperature) †	F	
12	TEMPERATURE OF FUEL	F	
13	GAS TEMP. LEAVING (Boiler) (Econ.) (Air Htr.)	F	
14	GAS TEMP. ENTERING AH (If conditions to be corrected to guarantee)	F	

UNIT QUANTITIES

15	ENTHALPY OF SAT. LIQUID (TOTAL HEAT)	Btu/lb	
16	ENTHALPY OF (SATURATED) (SUPERHEATED) STM.	Btu/lb	
17	ENTHALPY OF SAT. FEED TO (BOILER) (ECON.)	Btu/lb	
18	ENTHALPY OF REHEATED STEAM R. H. INLET	Btu/lb	
19	ENTHALPY OF REHEATED STEAM R. H. OUTLET	Btu/lb	
20	HEAT ABS/LB OF STEAM (ITEM 16 – ITEM 17)	Btu/lb	
21	HEAT ABS/LB R.H. STEAM (ITEM 19 – ITEM 18)	Btu/lb	
22	DRY REFUSE (ASH PIT + FLY ASH) PER LB AS FIRED FUEL	lb/lb	
23	Btu PER LB IN REFUSE (WEIGHTED AVERAGE)	Btu/lb	
24	CARBON BURNED PER LB AS FIRED FUEL	lb/lb	
25	DRY GAS PER LB AS FIRED FUEL BURNED	lb/lb	

HOURLY QUANTITIES

26	ACTUAL WATER EVAPORATED	lb/hr	
27	REHEAT STEAM FLOW	lb/hr	
28	RATE OF FUEL FIRING (AS FIRED wt)	lb/hr	
29	TOTAL HEAT INPUT $\frac{(\text{Item 28} \times \text{Item 41})}{1000}$	kB/hr	
30	HEAT OUTPUT IN BLOW-DOWN WATER	kB/hr	
31	TOTAL HEAT OUTPUT $\frac{(\text{Item 26} \times \text{Item 20}) + (\text{Item 27} \times \text{Item 21}) + \text{Item 30}}{1000}$	kB/hr	

FLUE GAS ANAL. (BOILER) (ECON) (AIR HTR) OUTLET

32	CO_2	% VOL	
33	O_2	% VOL	
34	CO	% VOL	
35	N_2 (BY DIFFERENCE)	% VOL	
36	EXCESS AIR	%	

FUEL DATA

	COAL AS FIRED PROX. ANALYSIS	% wt	
37	MOISTURE		
38	VOL MATTER		
39	FIXED CARBON		
40	ASH		
	TOTAL		
41	Btu per lb AS FIRED		
42	ASH SOFT TEMP.* ASTM METHOD		
	COAL OR OIL AS FIRED ULTIMATE ANALYSIS		
43	CARBON		
44	HYDROGEN		
45	OXYGEN		
46	NITROGEN		
47	SULPHUR		
40	ASH		
37	MOISTURE		
	TOTAL		

	OIL		
51	FLASH POINT F*		
52	Sp. Gravity Deg. API*		
53	VISCOSITY AT SSU* BURNER SSF		
44	TOTAL HYDROGEN % wt		
41	Btu per lb		
	GAS	% VOL	
54	CO		
55	CH_4 METHANE		
56	C_2H_2 ACETYLENE		
57	C_2H_4 ETHYLENE		
58	C_2H_6 ETHANE		
59	H_2S		
60	CO_2		
61	H_2 HYDROGEN		
	TOTAL		
	TOTAL HYDROGEN % wt		
62	DENSITY 68 F ATM. PRESS.		
63	Btu PER CU FT		
41	Btu PER LB		

COAL PULVERIZATION

48	GRINDABILITY INDEX*		
49	FINENESS % THRU 50 M*		
50	FINENESS % THRU 200 M*		

64 INPUT-OUTPUT EFFICIENCY OF UNIT % $\frac{\text{ITEM 31} \times 100}{\text{ITEM 29}}$

	HEAT LOSS EFFICIENCY	Btu/lb A. F. FUEL	% of A. F. FUEL
65	HEAT LOSS DUE TO DRY GAS		
66	HEAT LOSS DUE TO MOISTURE IN FUEL		
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2		
68	HEAT LOSS DUE TO COMBUST. IN REFUSE		
69	HEAT LOSS DUE TO RADIATION		
70	UNMEASURED LOSSES		
71	TOTAL		
72	EFFICIENCY = (100 – Item 71)		

* Not Required for Efficiency Testing

† For Point of Measurement See Par. 7.2.8.1-PTC 4.1-1964

CALCULATION SHEET

ASME TEST FORM FOR ABBREVIATED EFFICIENCY TEST

PTC 4.1-b (1964)

OWNER OF PLANT ..... TEST NO. ..... BOILER NO. ..... DATE .....

30 HEAT OUTPUT IN BOILER BLOW-DOWN WATER = LB OF WATER BLOW-DOWN PER HR × $\left[\frac{\text{ITEM 15} - \text{ITEM 17}}{1000}\right]$ kB/hr = ...

24 *If impractical to weigh refuse, this item can be estimated as follows*

DRY REFUSE PER LB OF AS FIRED FUEL = $\frac{\%\text{ ASH IN AS FIRED COAL}}{100 - \%\text{ COMB. IN REFUSE SAMPLE}}$

CARBON BURNED PER LB AS FIRED FUEL = $\frac{\text{ITEM 43}}{100} - \left[\frac{\text{ITEM 22} \times \text{ITEM 23}}{14.500}\right]$ = ...

NOTE: IF FLUE DUST & ASH PIT REFUSE DIFFER MATERIALLY IN COMBUSTIBLE CONTENT, THEY SHOULD BE ESTIMATED SEPARATELY. SEE SECTION 7, COMPUTATIONS.

25 DRY GAS PER LB AS FIRED FUEL BURNED = $\frac{11CO_2 + 8O_2 + 7(N_2 + CO)}{3(CO_2 + CO)}$ × (LB CARBON BURNED PER LB AS FIRED FUEL + $\frac{3}{8}$ S)

$$= \frac{11 \times \text{ITEM 32} + 8 \times \text{ITEM 33} + 7\left(\text{ITEM 35} + \text{ITEM 34}\right)}{3 \times \left(\text{ITEM 32} + \text{ITEM 34}\right)} \times \left[\text{ITEM 24} + \frac{\text{ITEM 47}}{2.67}\right] = ...$$

36 EXCESS AIR † = $100 \times \frac{O_2 - \frac{CO}{2}}{.2682N_2 - (O_2 - \frac{CO}{2})} = 100 \times \frac{\text{ITEM 33} - \frac{\text{ITEM 34}}{2}}{.2682\,(\text{ITEM 35}) - (\text{ITEM 33} - \frac{\text{ITEM 34}}{2})} = ...$

	HEAT LOSS EFFICIENCY	Btu/lb AS FIRED FUEL	$\frac{\text{LOSS}}{\text{HHV}} \times \frac{}{100}$ =	LOSS %
65	HEAT LOSS DUE TO DRY GAS = LB DRY GAS PER LB AS FIRED FUEL × C_p × ($t_{Ivg} - t_{air}$) = $\frac{\text{ITEM 25}}{\text{Unit}}$ × 0.24 (ITEM 13) − (ITEM 11) = ...	.....	$\frac{65}{41} \times 100$ =	.....
66	HEAT LOSS DUE TO MOISTURE IN FUEL = LB H_2O PER LB AS FIRED FUEL × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = $\frac{\text{ITEM 37}}{100}$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) − (ENTHALPY OF LIQUID AT T ITEM 11)] = ...	.....	$\frac{66}{41} \times 100$ =	.....
67	HEAT LOSS DUE TO H_2O FROM COMB. OF H_2 = $9H_2$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T GAS LVG) − (ENTHALPY OF LIQUID AT T AIR)] = 9 × $\frac{\text{ITEM 44}}{100}$ × [(ENTHALPY OF VAPOR AT 1 PSIA & T ITEM 13) − (ENTHALPY OF LIQUID AT T ITEM 11)] = ...	.....	$\frac{67}{41} \times 100$ =	.....
68	HEAT LOSS DUE TO COMBUSTIBLE IN REFUSE = ITEM 22 × ITEM 23 = ...	.....	$\frac{68}{41} \times 100$ =	.....
69	HEAT LOSS DUE TO RADIATION* = $\frac{\text{TOTAL BTU RADIATION LOSS PER HR}}{\text{LB AS FIRED FUEL} - \text{ITEM 28}}$	.....	$\frac{69}{41} \times 100$ =	.....
70	UNMEASURED LOSSES **	.....	$\frac{70}{41} \times 100$ =	.....
71	TOTAL	.....	.....	.....
72	EFFICIENCY = (100 − ITEM 71)	.....	.....	.....

† For rigorous determination of excess air see Appendix 9.2 – PTC 4.1-1964

* If losses are not measured, use ABMA Standard Radiation Loss Chart, Fig. 8, PTC 4.1-1964

** Unmeasured losses listed in PTC 4.1 but not tabulated above may by provided for by assigning a mutually agreed upon value for Item 70.

SECTION 2, SYMBOLS AND THEIR DESCRIPTIONS

2.1 Numerical Subscripts. The diagram of a steam generating unit, shown in Fig. 1, is intended to serve as a key to numerical subscripts employed throughout this Code to indicate the location to which reference is made. Many large installations will have all of the apparatus shown. Small industrial and commercial installations will be less elaborate. Even though the apparatus may not be in exactly the same relative position, it is believed that the numerical identification shown on this line diagram will prove applicable and helpful.

2.1.1 In the case of chemical symbols, the numerical subscripts refer to the number of atoms and not to the key diagram. The standard chemical symbols are used throughout this Code and are so well known that it is considered unnecessary to enumerate all of them.

2.1.2 When net efficiency is to be computed as outlined in Par. 6.2, it is necessary to determine certain values at points not indicated on Fig. 1. These items will carry subscripts higher than those shown on Fig. 1.

2.2 Symbols. A list of symbols for use in the computation is included at the end of this section. The chemical symbols are also used in some cases as subscripts.

2.2.1 With so many quantities and points of reference involved, it has been found impractical to restrict the Code to the use of single subscripts. Where both letter and numerical subscripts are used, the numerical one is given second; for example W_{se32}. This symbol means "W" for pounds, "s" for steam, "e" for elapsed time and "W_{se32}" then should be read "pounds of steam per hour at location 32 on Fig. 1" (Superheater outlet).

Symbols and Description

Symbol	Description	Unit
A	Air	. . . . .
A'	Dry Air	. . . . .
A.F.	As fired	. . . . .
API_{gr}	Gravity of the fuel based on the API scale	deg API
A_θ	Theoretical quantity of air required for complete combustion of the fuel	lb per lb of A.F. fuel
A_X	Excess air is the actual quantity of air used minus the theoretical air required divided by the theoretical air, and expressed as a percentage	per cent
a	Ash content of the fuel	per cent by weight
B	Heat credits added to the steam generator in the form of sensible heat	Btu
B_{Ae}	Sensible heat supplied by the entering air (rate)	Btu per hr
$B_{A'e}$	Sensible heat supplied by the *dry* entering air (rate)	Btu per hr
B_e	Heat credits added to the steam generator in the form of sensible heat (rate)	Btu per hr
B_{fe}	Sensible heat supplied with the fuel (rate)	Btu per hr
B_{mAe}	Heat supplied from the moisture entering with the inlet air (rate)	Btu per hr
B_{xe}	Heat supplied by auxiliary drives (rate)	Btu per hr
B_{ze}	Heat supplied by the atomizing steam (rate)	Btu per hr
b	Burned	. . . . .
C	Pounds of carbon per pound of "as fired" fuel – (laboratory analysis)	lb per lb of A.F. fuel
C_b	Pounds of carbon burned per pound of "as fired" fuel	lb per lb of A.F. fuel
CO	Per cent carbon monoxide per volume of dry flue gas. Determined by flue gas analysis	per cent
CO_2	Per cent carbon dioxide per volume of dry flue gas. Determined by flue gas analysis	per cent
CO_{2HC}	The pounds of carbon dioxide formed from burning the hydrocarbon in the dry flue gas	lb per lb of dry gas
c	Specific heat	Btu per lb F
c_p	Specific heat at constant pressure	Btu per lb F
$c_{pA'}$	Mean specific heat of dry air at constant pressure	Btu per lb F
c_{pd}	Mean specific heat at constant pressure for the flue dust over the temperature from the reference to the flue gas temperature	Btu per lb F

Symbols and Description (Cont'd)

Symbol	Description	Unit
c_{pf}	Mean constant pressure specific heat of the inlet fuel determined for temperature difference between fuel inlet temperature and reference temperature	Btu per lb F
c_{pG}	Mean specific heat of the flue gas	Btu per lb F
c_{ps}	Specific heat of steam	Btu per lb F
D	Standard or guarantee	. . . . .
d	Flue gas refuse (dust)	. . . . .
d'	Dry flue gas refuse (dust)	. . . . .
E	Energy	Btu
E_x	Energy consumed by auxiliaries	Btu
e	Elapsed time	hr
f	Fuel	. . . . .
G	Flue gas	. . . . .
G'	Dry flue gas	. . . . .
g	Gross	. . . . .
H	Pounds of hydrogen exclusive of that in moisture per pound of "as fired" fuel (laboratory analysis)	lb per lb of A.F. fuel
H_2	Hydrogen content of the flue gas (laboratory analysis)	cu ft per cu ft dry gas
HC	Per cent hydrocarbons per volume of dry flue gas (laboratory analysis)	per cent
$H_{d'p'}$	High-heat value of total dry refuse (laboratory analysis)	Btu per lb of refuse
H_{fp}	High-heat value of the fuel at constant pressure	Btu per lb
H_{fv}	High-heat value of the fuel at constant volume	Btu per lb
H_f	High-heat value (chemical heat) of the fuel on the "as fired" basis (laboratory analysis)	Btu per lb
$H_{f'}$	High-heat value (chemical heat) of the fuel on a dry basis (laboratory analysis)	Btu per lb
H_r	High-heat value (chemical heat) of the pulverizer rejects (laboratory analysis)	Btu per lb
h	Enthalpy	Btu per lb
h_{Rw}	Reference enthalpy of entering moisture. It is the enthalpy of the liquid at the reference temperature	Btu per lb
h_{Rv}	Reference enthalpy of entering vapor. It is the enthalpy of the saturated vapor at the reference temperature	Btu per lb
h_s	Enthalpy of steam	Btu per lb
h_{sx}	Enthalpy of steam supplied to any auxiliary steam drive	Btu per lb

Symbols and Description (Cont'd)

Symbol	Description	Unit
h_v	Enthalpy of the vapor	Btu per lb
h_w	Enthalpy of the liquid	Btu per lb
i	Isentropic process	. . . . .
K	Btu per cubic foot of dry flue gas (laboratory analysis)	Btu per cu ft of dry gas
(kwh)	Electrical energy	Kilowatt-hour
L	Heat loss from the steam generator which could have been added to the working fluid	Btu per lb of A.F. fuel
L_{CO}	Heat loss due to the formation of carbon monoxide	Btu per lb of A.F. fuel
L_d	Heat loss due to sensible heat in flue dust	Btu per lb of A.F. fuel
$L_{G'}$	Heat loss due to heat in dry flue gas	Btu per lb of A.F. fuel
L_H	Heat loss due to moisture from burning hydrogen	Btu per lb of A.F. fuel
L_{mA}	Heat loss due to moisture in the combustion air	Btu per lb of A.F. fuel
L_{mf}	Heat loss due to moisture in the "as fired" fuel	Btu per lb of A.F. fuel
L_p	Heat loss due to radiation to ashpit, sensible heat in slag and, if applicable, latent heat of fusion of slag	Btu per lb of A.F. fuel
L_r	Heat loss due to heat in pulverizer rejects	Btu per lb of A.F. fuel
L_{UC}	Heat loss due to unburned carbon	Btu per lb of A.F. fuel
L_{UH}	Heat loss due to unburned hydrogen	Btu per lb of A.F. fuel
L_{UHC}	Heat loss due to unburned hydrocarbons	Btu per lb of A.F. fuel
L_w	Heat loss due to heat rejected to cooling water used within the envelope Fig. 1	Btu per lb of A.F. fuel
L_z	Heat loss due to heat in the atomizing steam	Btu per lb of A.F. fuel
L_β	Heat loss due to radiation and convection	Btu per lb of A.F. fuel
M	Molecular weight of any substance	lb per mole
M_{HC}	Molecular weight of hydrocarbons	lb per mole

Symbols and Description (Cont'd)

Symbol	Description	Unit
m	Moisture content	per cent by weight
m_f	Moisture in fuel	lb of water per lb of A.F. fuel
m_p	Moisture in pit refuse	lb of water per lb of pit refuse
N	Pounds of nitrogen per pound of "as fired" fuel (laboratory analysis)	lb per lb of A.F. fuel
N_2	Per cent nitrogen per volume of dry flue gas. Determined by subtracting the sum of the measured quantities CO_2, O_2 and CO from 100	per cent
n	Net	. . . . .
O	Pounds of oxygen per pound of "as fired" fuel (laboratory analysis)	lb per lb of A.F. fuel
O_2	Per cent oxygen per volume of dry flue gas. Determined by flue gas analysis	per cent
P	Pressure	. . . . .
P_A	Atmospheric pressure	psia
P_f	Pressure of gaseous fuel at the primary measuring element	psia
P_{mA}	The partial pressure or vapor pressure of the moisture in the air	psia
P_{mG}	The partial pressure or vapor pressure of the moisture in the flue gas	psia
P_s	Pressure of the steam measured at the point indicated by the appropriate numerical subscript (Fig. 1)	psia
P_w	Pressure of the water measured at the point indicated by the subscript number (Fig. 1)	psia
p	Ashpit refuse	lb
$\boxed{p}$	Ashpit	. . . . .
p'	Dry pit refuse	lb
Q_{fe}	Quantity of gaseous fuel fired (rate) – based on 14.7 psia and 68 F. Note that the standard cu ft in the gas industry is based on 60 F and 14.73 psia	cu ft per hr
R	Reference	. . . . .
R_u	Universal gas constant (1545)	ft-lb/lb mole, deg R
r	Pulverizer rejects	lb
S	Pounds of sulfur per pound of "as fired" fuel (laboratory analysis)	lb per lb of A.F. fuel

Symbols and Description (Cont'd)

Symbol	Description	Unit
SO_2	Per cent sulfur dioxide per volume of dry flue gas (laboratory analysis)	per cent
s	Steam	. . . . .
T	Temperature Rankine	R
t	Temperature Fahrenheit	F
t_{RA}	Reference air temperature is the base temperature to which sensible heat losses and credits are compared for efficiency computations	F
t_A	Temperature of air	F
t_f	Temperature of fuel	F
t_G	Temperature of flue gas	F
t_s	Temperature of steam	F
t_w	Temperature of the water	F
U	Unburned	. . . . .
V	Volume of any substance – substance indicated by subscript	cu ft
v	Vapor	. . . . .
W	Weight	lb
W_A	Pounds of moist air supplied per pound of "as fired" fuel	lb per lb of A.F. fuel
$W_{A'}$	Pounds of dry air supplied per pound of "as fired" fuel	lb per lb of A.F. fuel
W_{Ae}	Pounds of air supplied (rate)	lb per hr
$W_{A'e}$	Pounds of dry air supplied (rate)	lb per hr
$W_{G'}$	The pounds of dry gas leaving unit per pound of "as fired" fuel	lb per lb of A.F. fuel
$W_{d'p'}$	Pounds of dry refuse per pound of "as fired" fuel	lb per lb of A.F. fuel
$W_{d'p'e}$	Pounds of dry refuse collected (rate)	lb per hr
W_{fe}	Pounds of fuel fired (rate) either solid or liquid	lb per hr
$W_{G'N_2}$	Pounds of nitrogen in dry gas per pound of "as fired" fuel	lb per lb
$W_{mA'}$	Pounds of moisture per pound of dry air	lb per lb of dry air
W_{se}	Pounds of steam per hour flowing at any location identified by appropriate numerical subscript	lb per hr
W_{sxe}	Pounds of steam supplied (rate) to all the steam driven auxiliaries	lb per hr
W_{we}	Pounds of water (rate)	lb per hr
W_z	Pounds of atomizing steam per pound of "as fired" fuel	lb per lb of A.F. fuel

Symbols and Description (Cont'd)

Symbol	Description	Unit
w	Water	. . . . .
X	Excess	. . . . .
x	Auxiliary	. . . . .
z	Atomizing steam	. . . . .
β	Radiation and convection	. . . . .
γ	Gas specific weight at 68 F and 14.7 psia	lb per cu ft of gas
δ	Corrected	. . . . .
η	Efficiency	per cent
η_g	Gross efficiency	per cent
η_n	Net efficiency	per cent
η_x	Efficiency of auxiliary drives	per cent
θ	Theoretical	. . . . .
ψ	The number of pound moles of any substance — substance indicated by subscript	. . . . .
$'$ (prime)	Dry	. . . . .
Δ	Change	. . . . .

2.3 Test and Run. Throughout this Code the word "test" is applied only to the entire investigation, and the word "run" to a subdivision. A run consists of a complete set of observations made for a period of time with one or more of the independent variables maintained virtually constant.

SECTION 3, GUIDING PRINCIPLES

3.01 Items on Which Agreement Shall be Reached. In order to achieve the objectives of the test the interested parties must reach agreement on the following pertinent items:

3.01.01 Gross efficiency determination – Defined in Par. 1.06.

3.01.01.1 General method – Heat loss or input-output.

3.01.01.2 Heat credits to be measured.

3.01.01.3 Heat credits to be assigned where not measured.

3.01.01.4 Heat losses to be measured.

3.01.01.5 Heat losses to be assigned where not measured.

3.01.01.6 Permissible deviation in efficiency between duplicate runs.

3.01.02 Capacity or Output – Defined in Par. 1.05.

3.01.03 Other related operating characteristics – See Section 8.

3.01.04 Allocation of responsibility for all performance and operating conditions which affect the test.

3.01.05 Selection of test personnel to conduct the test.

3.01.06 Establishment of acceptable operational conditions, number of load points, duration of runs, basis of rejection of runs and procedures to be followed during the test.

3.01.07 Cleanliness of unit initially and how this is to be maintained during the test. See Par. 3.04.2.

3.01.08 Actual air leakage to be allowed, if any, initially or during the test.

3.01.09 The source of thermodynamic properties to be used. Sources such as "Thermodynamic Properties of Steam" by Keenan and Keyes, and ASME Supplement thereto, and "Vapor Charts" by Ellenwood and Mackey are acceptable.

3.01.10 The fuel to be fired, the method of obtaining fuel samples and the laboratory to make the analysis.

3.01.11 Observations and readings to be taken to comply with the object or objectives of the test.

3.01.12 Instruments to be used, calibration of instruments, methods of measurement and equipment to be used in testing the unit. The Power Test Code Supplements on Instruments and Apparatus should be used, when applicable.

3.01.13 Tolerances and limits of error in measurement and sampling.

3.01.14 Distribution of fuel refuse quantities between various collection points and methods of sampling.

3.01.15 Corrections to be made for deviations from specified operating conditions.

3.02 Selection of Personnel. To insure obtaining reliable results, all personnel participating in the test shall be fully qualified to perform their particular function.

3.03 Tolerances and Limits of Error. This Code does not include consideration of over-all tolerances or margins on performance guarantees. The test results shall be reported as computed from test observations, with proper corrections for calibrations.

3.03.1 Allowances for errors of measurement and sampling are permissible provided they are agreed upon in advance by the parties to the test and clearly stated in the test report. The limits of probable error on calculated steam generator efficiency, shall be taken as the square root of the sum of the squares of the individual effects on efficiency.

3.03.2 Whenever allowances for probable errors of measurement and sampling are to be taken into consideration, the reported test results shall be qualified by the statement that the error in the results may be considered not to exceed a given plus or minus percentage, this value having been determined in accordance with the foregoing method for computing limits of probable error.

3.03.3 The following table is included as a guide to show the effect on efficiency of measurement errors exclusive of sampling errors. The measurement error range in the table is not intended to be authoritative but conforms approximately with experience. The values in the table are not intended to be used in any calculation of test results.

PROBABLE MEASUREMENT ERRORS AND RESULTING ERRORS IN EFFICIENCY CALCULATIONS

3.03.4 I – Input-Output Method

Measurement	Measurement error, per cent	Error in calculated Steam Generator Efficiency, per cent
(1) Weigh tanks (calibrated scales)	±0.10	±0.10
(2) Volumetric tanks (calibrated)	±0.25	±0.25
(3) Calibrated flow nozzle or orifice including manometer	±0.35	±0.35
(4) Calibrated flow nozzle or orifice including recorder	±0.55	±0.55
(5) Coal scales – Batch or dump (calibrated)	±0.25	±0.25
(6) Uncalibrated flow nozzle or orifice including manometer	±1.25	±1.25
(7) Uncalibrated flow nozzle or orifice including recorder	±1.60	±1.60
(8) Fuel heating value (coal)	±0.50	±0.50
(gas and oil)	±0.35	±0.35
(9) Reheat flow (based on heat balance calculations)	±0.60	±0.10
(10) Superheater outlet temperature (calibrated measuring device)	±0.25	±0.15
(11) Superheater outlet pressure (calibrated measuring device)	±1.00	±0.00
(12) Reheater inlet and outlet temperature (calibrated measuring device)	±0.25	±0.10
(13) Reheater inlet and outlet pressure (calibrated measuring device)	±0.50	±0.00
(14) Feedwater temperature (calibrated measuring device)	±0.25	±0.10

3.03.5 II – Heat Loss Method

Measurement	Measurement error, per cent	Error in calculated Steam Generator Efficiency, per cent
(1) Heating value (coal)	±0.50	±0.03
(gas and oil)	±0.35	±0.02
(2) Orsat analysis	±3.00	±0.30
(3) Exit gas temperature (calibrated measuring device)	±0.50	±0.02
(4) Inlet air temperature (calibrated measuring device)	±0.50	±0.00
(5) Ultimate analysis of coal (carbon)	±1.00	±0.10
(hydrogen)	±1.00	±0.10
(6) Fuel moisture	±1.00	±0.00

3.04 Acceptance Test. An acceptance test shall be undertaken only when the parties to the test certify that the unit is operating to their satisfaction and is, therefore, ready for test. Especially in the case of fuel burning equipment, adjustments and changes are sometimes necessary to obtain optimum performance. The acceptance test should be started as soon as the unit is in satisfactory condition for test, provided the load and other governing factors are suitable.

3.04.1 Parties to the test may designate a person to direct the test and to serve as arbiter in the event of disputes as to the accuracy of observations, conditions or methods of operation, see Par. 8.04.1.

3.04.2 All heat transfer surfaces, both internal and external, should be commercially clean (normal operating cleanliness) before starting the test, refer to Par. 3.01.7. During the test, only the amount of cleaning shall be permitted as is necessary to maintain normal operating cleanliness.

3.04.3 After a preliminary run has been made, it may be declared an acceptance run if agreed to and provided that all the requirements of a regular run have been met.

3.04.4 At least two runs shall be made approximating the load required for acceptance. If the results exceed the previously agreed upon deviation in efficiency between runs, a third run will be required. The test efficiency at the required load will be the average of the two runs which fall within the permissible deviation in efficiency.

3.05 Preparation for All Tests.

3.05.1 The entire steam generating unit shall be checked for leakage. Air heater internal leakage shall also be checked. Excessive leakage shall be corrected.

3.05.2 Before the test is started, it shall be determined whether the fuel to be fired is substantially as intended.

3.05.3 Any departures from standard or previously specified conditions in physical state of equipment, cleanliness of heating surfaces, fuel characteristics, or constancy of load, shall be described clearly in the report of the test.

3.06 A Preliminary Run shall be made for the purpose of:

3.06.1 Checking the operation of all instruments.

3.06.2 Training the observers and other test personnel.

3.06.3 Making minor adjustments, the needs for which were not evident during the preparation for the test, and establishing proper combustion con-

ditions for the particular fuel and rate of burning to be employed.

3.07 Starting and Stopping. Combustion conditions, rate of feeding fuel (also quantity of fuel on grate if stoker fired), rate of feeding water, water level in drum (if of drum type), excess air and all controllable temperatures and pressures shall be, as nearly as possible, the same at the end of the run as at the beginning. These, and any other conditions in which variations might affect the results of the test, shall be essentially reached and held as constant as possible. There must be reasonable assurance that the temperature of the refractories of the setting and all other parts of the equipment have reached equilibrium before the run is started. The time required to attain stabilization or equilibrium with respect to temperatures will vary widely with the design of the unit and character of materials in the setting. This period of stabilization can vary from a minimum of one hour to more than three hours.

3.07.1 In some instances it may be necessary to terminate a run prematurely because of inability to maintain one or more of the operating conditions at the desired value.

3.07.2 In order to attain the desired operating conditions when solid fuel is fired by stokers, it is essential that major cleaning and conditioning of the fuel bed shall be accomplished some length of time before the run starts and again the same length of time before the run is completed. Minor occasional normal cleaning of the fuel bed may be permitted during the run. Rate of burning or feeding fuel after the initial cleaning of fires shall be kept at that rate which is to prevail during the run. The fuel bed depth shall be the same at the beginning and end of the run. The ashpit shall be emptied either just after the initial and final cleaning and conditioning of the fuel bed or just before the start and end of the run so that the weight of refuse corresponds to the weight of coal burned.

3.07.3 In the case of runs to determine the maximum output at which the unit can be operated for a short period, the run should be started as soon as the maximum output is reached and continued until conditions necessitate terminating the run.

3.08 Duration of Runs.

3.08.1 When determining the efficiency of coal fired units, using pulverized coal or crushed coal as in the case of cyclone firing, the runs should be preferably of not less than four hours duration. This duration is satisfactory even for tests conducted by the input-output method provided a unit system of pulverizers or crushers is used, and the fuel weighed as it is fed to the pulverizers or crushers. For those stations having a centralized fuel preparation plant, it may be impractical to weigh the fuel fed to any one unit, in which case the loss method should be used.

3.08.2 When determining the efficiency of a stoker fired steam-generating unit by input-output, the runs should be preferably of twenty-four hours duration. However, in the case of continuous ash discharge stokers, if conditions make it advisable, the length of a run may be reduced, but not to less than ten hours. The longer the duration of the runs the less will be the possibility of significant error due to estimating the difference in amount of unburned fuel on the grate at the beginning and end of the run. In many cases it is difficult to estimate the change in thickness of a large fuel bed closer than three inches. When the ratio of ash to unburned fuel is also indeterminate, the final estimate of effective change in bed thickness will frequently be in error by as much as four inches. The possible error due to estimating the effective change in the amount of unburned fuel on the grate at the beginning and end of each run should be considered in determining the duration of each run. Runs by heat loss method shall be of at least four hours duration.

3.08.3 When determining the efficiency of steam generating units fired with liquid or gaseous fuels, the runs should preferably be of not less than four hours duration.

3.08.4 For waste heat boilers, efficiency runs shall be for not less than four hours duration.

3.08.5 The duration of runs to determine the maximum short period output, when the efficiency is not to be determined, shall be by agreement of the parties to the test.

3.08.6 The actual duration of all runs from which the final test data are derived shall be clearly stated in the test report.

3.09 Performance Curves. It is desirable, but not mandatory, that runs be made at not less than four different outputs, so that curves may be drawn to relate the test points. Such curves, showing

pertinent test data, plotted against output, are very useful in appraising the performance of the unit, because the desired outputs are seldom exactly obtained during the test. Where there are enough test points to establish characteristic curves, the performance at any output may be read from the curves.

3.10 Frequency and Consistency of Readings. Except for quantity measurements, the readings shall be taken at 15 minute intervals. If, however, there are fluctuations, the readings shall be taken at such frequency as may be necessary to determine the average.

3.10.1 Where the amount of fuel or feedwater is determined from integrating instruments, a reading shall be taken every hour. If the quantities to be determined are weighed, the frequency of weighing is usually determined by the capacity of the scales, but the intervals shall be such that a total can be obtained for each hour of the test. The time shall be recorded when each hopper of coal or each tank of feedwater is dumped. When indicating flowmeters or manometers are used with venturi tubes, flow nozzles or orifice plates for subsequently determining quantity measurements, the flow indicating element shall be read at five minute intervals or more frequently when deemed necessary.

3.10.2 It is suggested that, in so far as feasible, pertinent data of the run be plotted continuously, as the run progresses, on coordinate paper of suitable scale arrangements to permit a complete review of the conduct of the run at least hourly.

3.11 Rejection of Runs. Should serious inconsistencies in the observed data be detected during a run or during the computation of the results, the run shall be rejected completely, or in part if the affected part is at the beginning or at the end of the run. A run that has been rejected shall be repeated, if necessary to attain the objectives of the test.

3.12 Records and Test Reports. All observations, measurements and instrument readings necessary for the objective of the test shall be recorded as observed. Corrections and corrected values shall be entered separately in the test record.

3.13 Instruments and Methods of Measurement. The necessary instruments and procedures for making measurements are prescribed herein and should be used in conjunction with the following ASME Power Test Codes Supplements on Instruments and Apparatus, and other publications for detailed specifications on apparatus and procedures involved in the testing of steam-generating units. In all cases, care shall be exercised to refer to the latest revision of the document concerned.

3.13.1 ASME Power Test Codes:
- General Instructions PTC 1
- Definitions and Values PTC 2
- Diesel and Burner Fuels PTC 3.1
- Solid Fuels PTC 3.2
- Gaseous Fuels PTC 3.3
- Coal Pulverizers PTC 4.2
- Air Heater PTC 4.3
- Centrifugal, Mixed Flow and Axial Flow Compressors and Exhausters PTC 10
- Fans PTC 11
- Dust Separating Apparatus PTC 21
- Determining Dust Concentration in a Gas Stream PTC 27

3.13.2 Supplements on Instruments and Apparatus PTC 19:
- Part 1, General Considerations PTC 19.1
- Part 2, Pressure Measurement PTC 19.2
- Part 3, Temperature Measurement PTC 19.3
- Part 5, Measurement of Quantity of Materials PTC 19.5
- Part 6, Electrical Measurements in Power Circuits PTC 19.6
- Part 10, Flue and Exhaust Gas Analyses PTC 19.10
- Part 11, Determination of Quality of Steam PTC 19.11
- Part 12, Measurement of Time PTC 19.12
- Part 13, Measurement of Rotary Speed PTC 19.13
- Part 16, Density Determinations PTC 19.16
- Part 17, Determination of Viscosity of Liquids PTC 19.17
- Part 18, Humidity Determinations PTC 19.18
- Part 21, Leakage Measurement PTC 19.21

3.13.3 ASME Research Publication:
- Fluid Meters – Their Theory and Application

3.13.4 American Gas Association:
Orifice Metering of Natural Gas – Gas Measurement Committee Report No. 3, April, 1955

3.13.5 ASTM Standard Methods:
Methods of Sampling Coals, D 492
Laboratory Sampling and Analysis of Coal and Coke, D 271
Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter, D 240
Test for Calorific Value of Gaseous Fuel by the Water-Flow Calorimeter, D 900

3.13.6 National Bureau of Standards:
Methods of Measuring Humidity and Testing Hygrometers, Circular 512

SECTION 4, EFFICIENCY BY INPUT-OUTPUT METHOD

4.01 Determination of Steam Generator Efficiency by Input-Output Method. This method is based on the ratio of the output, to the sum of the fuel input plus heat credits. It requires accurate measurement of the quantity and high-heat value of the fuel and the heat absorbed by the steam generator.

Input Measurement

4.02 The following paragraphs describe the methods of determining the steam generator input. These methods shall be used when evaluating the steam generator by the input-output method.

4.03 Solid Fuel-Quantity Measurement. Fuel shall be weighed near the point where it is to be used. All loss of fuel between the point of weighing and the point of introduction to the steam generating unit shall be measured and accounted for. The weighing scales shall be calibrated prior to and after the test. Experience indicates a possible measurement error within 0.25 per cent in the range of loads weighed. Checks and calibrations shall be made in accordance with I & A, Measurement of Quantity of Materials PTC 19.5, Chapter 1.

4.03.1 Arrangement and operation of fuel weighing equipment shall preferably be such that checks can be made on consumption during each hour of the run as a matter of convenience and guide. Only the totals, however, are to be used in the final calculations.

4.04 Solid Fuel Sampling. A representative sample of fuel shall be obtained in accordance with the Test Code for Solid Fuels PTC 3.2.

4.04.1 "Because of the many variations in the conditions under which coal must be sampled, and the nature of the material being sampled, it is essential that the samples be collected by a trained and experienced sampler. Variations in the manner in which the coal is handled are such that it is impossible to specify rigid rules describing the exact manner of sample collection. Correct sampling principles must be applied to conditions as they are encountered.

4.04.2 "The first principle of coal sampling for a boiler test is to obtain the sample from a moving stream. The second principle is to obtain as many increments as is practical. The ASTM increments listed under Section 5, Special Purpose Sampling Procedure, should be considered the minimum accepted for fairly uniform coal from one source."*

4.04.3 The special sample for moisture determination shall be separated from the general sample, quickly placed in a non-corrosive air tight container and sealed immediately. This sample for moisture shall not be quartered or crushed prior to moisture determination in the laboratory. Every effort shall be made to avoid loss of moisture due to strong drafts at the point of sampling (such as may occur at a pulverizer feeder for example).

4.05 Solid Fuel Analysis and High-Heat Value. Fuel analysis and high-heat value determination shall be made in accordance with the Test Code for Solid Fuels PTC 3.2 and ASTM Standard Methods of Laboratory Sampling and Analysis of Coal and Coke, ASTM D 271. This is a constant volume determination. However, the fuel is burned at constant pressure in the steam generator, and therefore, the high-heat value at constant volume as determined in the bomb calorimeter must be converted to a constant pressure high-heat value. See Par. 7.2.6.2. This high-heat value for constant pressure combustion is referred to as the high-heat value throughout this Code. When testing in accordance with the input-output method, only the high-heat value and the moisture content of the fuel are required.

4.06 Liquid Fuel – Quantity Measurement. The preference for this measurement is by means of calibrated weigh tanks. If such facilities are not available then calibrated volumetric tanks should be used. Experience indicates the former to have a possible measurement error within ± 0.10 per cent and the latter within ± 0.25 per cent. Calibrations and handling of the tanks during tests should be such as to obtain these accuracies. Positive displacement meters may be used if carefully calibrated under conditions simulating those existing during the test in regard to grade of fuel,

*Material under quotation marks is from ASTM D 492-48 Method of Sampling Coals.

temperature, pressure, rate of flow and meter location. Calibrated meter accuracy must be within ±0.50 per cent.

4.06.1 Leakage of fuel between point of measurement and point of firing shall be measured and accounted for in the flow calibration. Branch connections on the fuel piping shall be either blanked off or provided with double valves and suitable telltale drains for detecting leakage. Leakage from valve stuffing boxes shall be prevented. Any unavoidable leakage from pump stuffing boxes, or elsewhere, shall be collected and accounted for. Where an oil return system from the burners is used, both supply and return flows shall be measured by calibrated meters.

4.06.2 Practice and precautions relative to the use of weigh tanks and volumetric tanks for liquid fuel measurement shall be those stated in Pars. 4.14 and 4.15.

4.07 Liquid Fuel-Sampling. A representative sample of fuel shall be obtained in accordance with the Test Code for Diesel and Burner Fuels PTC 3.1.

4.08 Liquid Fuel Analysis and High-Heat Value. Fuel analysis, high-heat value, density and viscosity determination shall be made in accordance with the Test Code for Diesel and Burner Fuels PTC 3.1, ASTM Standard Methods for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter D 240, Density Determinations PTC 19.16 and Determination of the Viscosity of Liquids PTC 19.17. This is a constant volume determination. However, the fuel is burned at constant pressure in the steam generator and, therefore, the high-heat value at constant volume as determined in the bomb calorimeter must be converted to a constant pressure high-heat value. See Par. 7.2.6.2. This high-heat value for constant pressure combustion is referred to as the high-heat value throughout this Code.

4.09 Gaseous Fuel – Quantity Measurement. Measurement of the relatively large volumes of gaseous fuel normally encountered in testing steam generators requires the use of the orifice, flow nozzle or venturi. The measuring device shall be calibrated prior to and after the test. For probable measurement errors see Par. 3.03.4.

4.09.1 The recommendations of I & A, PTC 19.5, Chapter 4, shall be followed with reference not only to the design, construction, calibration and use of flow measuring elements, but also to their location and installation in the pipe line and the installation of the connecting piping system between the primary element and manometer. All computations of flow rate from the observed differentials, pressures and temperatures shall be made in accordance with the provisions of PTC 19.5, Chapter 4. Where natural gas is used, it may be advantageous to use the method and procedure of "Orifice Metering of Natural Gas." See Par. 3.13.4.

4.09.2 If fluctuations in flow are present, due to reciprocating devices or other source of pulsation, the difference between the indicated maximum and minimum flow rates shall be minimized and must be made to be less than ±5 per cent of the average flow, by the introduction of a cushion chamber, surge chamber, or other means of absorbing the pulsations between the source of pulsation and the primary device, before measurement is considered acceptable. For further discussion of pulsating flow measurement see ASME Research Publication: Fluid Meters – Their Theory and Application – Pars. 106 to 109, inclusive.

4.09.3 Pressure of the gaseous fuel at point of volume determination and at other required points shall be measured by a suitable manometer or pressure gage as described in Instruments and Apparatus, Pressure Measurement PTC 19.2. Temperature shall be measured with thermometers in accordance with I & A Temperature Measurement PTC 19.3, Chapter 5 on Liquid-in-Glass Thermometers.

4.10 Gaseous Fuel-Sampling. The gas shall be properly sampled in accordance with the Test Code for Gaseous Fuels PTC 3.3.

4.11 Gaseous Fuel Analysis and High-Heat Value. Fuel analysis and high-heat value determination shall be made in accordance with the Test Code for Gaseous Fuels PTC 3.3 and ASTM Standard Methods of Test for Calorific Value of Gaseous Fuels by the Water-Flow Calorimeter D 900 or Tentative Method of Test for Calorific Value of Gases in Natural Gas Range by Continuous Recording Calorimeter, ASTM D 1826.

4.12 Heat Credits. Heat credits are sensible heats added to the steam generator envelope Fig. 1 and are listed in Fig. 2. Heats of each are

determined by a quantity measurement multiplied by an enthalpy difference, or by the conversion to thermal units if an electrical energy measurement.

Output Measurement

4.13 The method of measuring output flow in connection with the input-output method is to measure the water flow into the unit as outlined in Pars. 4.14, 4.15 and 4.16 and also as given in PTC 6, Test Code for Steam Turbines. These are the only accepted test measurements of output flow.

4.14 Weigh Tanks. Suitable tanks and scale shall be calibrated prior to and after the test and caused to weigh to a possible measurement error within ±0.10 per cent in the range of loads weighed. The weight of water used must be corrected for any steam or condensate entering or leaving the cycle, after the weigh point. A heat balance diagram shall be prepared to reveal additional sources of supply, if any, to the feedwater circuit.

4.14.1 Design, construction, calibration and operation of weighing tanks shall be in accordance with I & A Measurement of Quantity of Materials PTC 19.5.

4.15 Volumetric Tanks. Volumetric tanks shall be calibrated prior to and after the test and caused to measure a possible measurement error within ±0.25 per cent in the range of loads measured.

4.15.1 Volumetric tanks shall be calibrated with weighed increments of water at a constant temperature and measurement accuracy of ±2 F. In the use of volumetric tanks, density corrections shall be made for water temperature differences during testing and calibration. Corrections shall also be made for the change in thermal expansion of the tank metal.

4.15.2 The precautions given in Par. 4.14 shall be observed wherever they apply to volumetric tanks.

4.15.3 Design, construction, calibration and operation of volumetric tanks shall be in accordance with I & A Measurement of Quantity of Materials PTC 19.5.

4.16 Venturi Tube, Flow Nozzle or Thin Plate Orifice. Water quantity may be measured by venturi tube, flow nozzle or thin plate orifice. Measuring devices including manometers shall be calibrated prior to and after the test and caused to measure to an accuracy within ±0.35 per cent in the range of loads measured.

4.16.1 The recommendations of I & A Measurement of Quantity of Materials PTC 19.5, Chapter 4, shall be followed with reference not only to the design, construction, calibration and use of flow measuring elements, but also to their location and installation in the pipe lines and the installation of the connecting piping system between the primary element and the manometer. All computations of flow rate from the observed differentials, pressures and temperatures shall be made in accordance with the provisions of PTC 19.5, Chapter 4.

4.16.2 Venturi tube, nozzle or orifice selected shall be such that the differential pressure at any test output as shown by the manometer is at least five inches of manometric liquid. See PTC 19.5, Chapter 4.

4.16.3 If fluctuations in flow are present, due to reciprocating devices or other source of pulsation, the difference between the indicated maximum and minimum flow rates shall be reduced to not more than ±5 per cent of the average flow by the introduction of a cushion chamber, surge chamber or other means of absorbing the pulsations between the source of pulsation and the primary device, before measurement is considered acceptable. For further discussion of the pulsating flow measurement see ASME Research Publication: Fluid Meters – Their Theory and Application, Pars. 106 to 109, inclusive.

4.16.4 Differential pressure at the primary metering element shall be measured by two complete manometer systems which shall agree within ±0.2 per cent of each other. Both manometers of a two-manometer system shall be in accordance with I & A, Pressure Measurement PTC 19.2, Chapter 3.

4.17 Flow Measurement of Steam. Output steam flow to be used in the input-output method must be obtained from feedwater measurement as described in Pars. 4.14, 4.15 and 4.16 and Test Code for Steam Turbines PTC 6 corrected for any addition or withdrawal of fluid beyond the measuring element, such as continuous blowdown, desuperheating spray water, boiler circulating pump injection water, etc.

4.17.1 For determining capacity or other related operating characteristics, the output quantity of the main and reheat steam may be determined by means of nozzles or thin plate orifices. Steam line pressure drops may be used for this purpose if they have been previously calibrated.

4.17.2 Reheat steam flow can be computed by subtracting appropriate extraction steam, high pressure turbine leakage and auxiliary steam from the main steam flow and adding desuperheater flow when latter is used. See PTC 6 for example.

4.17.3 The recommendations of I & A Measurement of Quantity of Materials PTC 19.5, Chapter 4, shall be followed with reference not only to the design, construction, calibration and use of flow nozzles and orifices, but also to their location and installation in the pipe line and the installation of the connecting piping system between the primary element and the manometer. All computations of flow rate from the observed differential pressures and temperatures shall be made in accordance with the provisions of Measurement of Quantity of Materials PTC 19.5, Chapter 4.

4.17.4 Differential pressures at the primary metering element shall be measured by a direct reading manometer system.

4.18 Precautions and Corrections Relating to Output Quantity Measurements. All leakage which may affect test results shall be eliminated. If not eliminated, it must be measured and accounted for. Errors due to steam or water entering or leaving the equipment under test, through connecting piping, shall be prevented by blanking off such connections or by providing open telltale drains between double valves to give visible assurance that no flow exists. Leakage tests shall be made in accordance with I & A, Leakage Measurement PTC 19.21.

4.18.1 Water content of all locations where water can accumulate between point of measurement and the boiler, such as surge tanks, feedwater heaters and receiving tanks to which measuring tanks discharge, shall be recorded at the start and conclusion of the run and proper allowances made.

4.18.2 Blowing down during a run shall preferably be avoided. If this is not possible, the amount of heat can be determined by heat balance around the blowdown heat recovery system. Corrections shall be made for any steam and water which are sampled for the determination of solids or for chemical analysis.

4.18.3 Soot blower operation during a run should either be avoided or allowance made.

4.19 Steam and Feedwater Temperatures. Saturated steam temperature may be measured at any point in the steam line where convenient but as close to the saturated steam outlet as possible. The temperature of superheated steam shall be measured as close to the superheater and/or reheater outlets as possible to minimize error from heat loss. Feedwater temperatures shall be measured as close to the economizer inlet and boiler inlet as possible. Steam and feedwater temperatures which are of primary importance shall each be taken at two different points as close together as practical and the mean of the two readings after corrections to each shall be the temperature of the fluid. Discrepancies between the two corrected readings exceeding 0.25 per cent for steam and 0.50 per cent for water shall be investigated.

4.19.1 Mercury-in-glass thermometers, resistance thermometers or thermocouples are acceptable for temperatures up to 700 F. At or above 700 F either resistance thermometers or thermocouples shall be used.

4.19.2 All temperature measuring devices shall be calibrated before and after tests. When employing mercury-in-glass thermometers, proper allowance shall be made for differences between thermometer stem temperature during calibration and test. See I & A, Temperature Measurement PTC 19.3.

4.19.3 The following precautions shall be observed in the use of temperature measuring devices.

4.19.3.1 All temperature measuring instruments and wells shall be constructed, installed, and the instruments calibrated and operated in accordance with I & A Temperature Measurement PTC 19.3.

4.19.3.2 Temperature measuring devices shall be installed so that they will not be affected by radiation or conduction.

4.19.3.3 The heat receiving part of the instrument shall not be located in a dead pocket of the fluid, the temperature of which is a subject of measurement.

4.20 Moisture in Steam. Moisture in steam at saturation temperature in connection with output determination shall be measured with a suitable calorimeter constructed, installed and operated in the manner described in I & A, Methods for Determination of Quality and Purity of Steam PTC 19.11.

4.21 Steam and Feedwater Pressures. Pressure gages shall be located where they will not be affected by any disturbing influences such as extremes of heat and cold and vibration and shall be located in convenient positions for reading. While calibrated Bourdon test gages or deadweight gages may be used, the use of the latter is preferred.

4.21.1 Gage connections shall be as short and direct as possible.

4.21.2 Gages shall be protected with syphons or their equivalent. Convolutions of syphons shall be as few in number as possible, consistent with the gage remaining cool, because of their tendency to introduce errors due to unbalanced water columns in the convolutions.

4.21.3 All gage connections shall be tight.

4.21.4 Pressure connections shall be located and installed with extreme care in order to avoid errors due to impact and eddies. Pressure gage pulsations shall not be dampened by throttling the connection to the gage or by the use of commercial gage dampers, but a volume chamber may be employed. The arrangement may be considered satisfactory if the maximum and minimum values of the instantaneous pressure do not differ by more than 2.0 per cent from the mean value. Bourdon test gages shall be calibrated, installed and used in accordance with I & A, Pressure Measurement PTC 19.2. These gages shall be calibrated before and after the test and at intervals of not more than one week if the test is extended beyond that period.

SECTION 5, EFFICIENCY BY HEAT LOSS METHOD

Definition and Data

5.01 Steam Generator Efficiency by Heat Loss Method. This method is based upon accurate and complete information which will make possible the calculations to determine all accountable losses and heat credits. The efficiency then is equal to 100 per cent minus a quotient expressed in per cent. The quotient is made up of the sum of all accountable losses as the numerator, and heat in the fuel plus heat credits, as the denominator. The capacity at which the unit is to be tested may be based upon either water flow measurement in accordance with Pars. 4.14, 4.15 and 4.16 or steam flow measurement in accordance with Par. 4.17.

5.02 Data Required. Accurate data on the following items are required:

5.02.1.01 Fuel analysis.

5.02.1.02 Flue gas composition or analysis for CO_2, O_2, CO and other gaseous combustibles.

5.02.1.03 Flue gas temperature determined as result of a velocity and temperature traverse of the cross sectional area.

5.02.1.04 Temperature of air supplied to unit for combustion.

5.02.1.05 Combustible content and quantity of dust carried by exit gases.

5.02.1.06 Combustible content and respective quantities in dust collector hoppers and all miscellaneous hoppers.

5.02.1.07 Combustible content and quantity of ashpit refuse.

5.02.1.08 Temperature of fuel supplied at point entering unit.

5.02.1.09 Temperature pressure and quantity of any medium used for operation of the boiler, such as water for cooling doors, atomizing steam, circulating water for pump glands, etc.

5.02.1.10 Humidity of air supplied for combustion.

5.02.1.11 Radiation.

5.02.1.12 Sensible heat in flue dust.

5.02.1.13 Ashpit heat loss.

5.02.1.14 Pyrites (pulverizer rejects).

5.02.1.15 Electric power for gas recirculation fans, boiler circulating water pumps, primary air fans, pulverizers and crushers. See Par. 6.1.1.2.

5.02.2 With the above information accurately obtained, all losses on the unit can be calculated in terms of per cent of the sum of the high-heat value of the "as fired" fuel plus heat credits. Equations for calculating all losses and credits are given in Section 7.

Fuel Sampling and Analysis

5.03 The accuracy of the heat loss method depends upon an accurate sample and ultimate analysis of the fuel being fired. The analysis should break the fuel constituents into the various chemical elements which are combustible or take part in the chemical reaction. These elements are determined in per cent by weight or per cent by volume of the "as fired" fuel. Refer to Fuel Sampling and Analysis, Section 4 of this Code, and Power Test Codes; Diesel and Burner Fuels PTC 3.1, Solid Fuels PTC 3.2, and Gaseous Fuels PTC 3.3.

Flue Gas Sampling and Analysis

5.04 Sampling Locations. Orsat analysis of the flue gases at the exit of the steam generator is required. This will be at locations 15, 14 or 12, Fig. 1 depending upon the equipment which comprises the steam generator. Frequently analyses are required at other points. There may be considerable variation in flue gas analysis over the cross section of the gas passage due to stratification and air infiltration. The best practical method of obtaining representative results is to divide the cross section of the gas passage into equal areas and to take velocity measurements and simultaneous gas samples from the centers of these component areas. A weighted average can then be calculated, taking into consideration the gas temperature, Par. 5.08, as well as the velocity. The number and arrangement of the equal areas will depend on the size and configuration of the gas passage. The areas shall be approximately square and the sampling points shall be not more than 3 feet apart, and a total of

not less than four points shall be used. In round ducts, test points shall be located on two traverses along axes normal to each other. It is recognized that there may be cases in which the gas velocity is so low that velocity measurements would be impractical. In such cases an arithmetic average rather than a weighted average should be employed. Where accuracy is not impaired, an aspirator and suitable apparatus for obtaining a composite sample from several sampling points may be employed. With the exception of the area sampling instruction above, all of the procedures are to be in accordance with recommendations of I & A, Flue and Exhaust Gas Analyses PTC 19.10.

5.05 Sampling Lines. Sampling tubes shall be made of material which shall not contaminate the sample by the temperatures encountered. For sampling high temperature flue gas, such as in a furnace or at the gas entrance to a waste heat boiler, suitable water cooled samplers must be employed. Sampling lines shall be as short and straight as possible, shall be accessible for cleaning and blowing out, shall slope in the direction of the flow, shall be suitably drained and shall be maintained tight. All sampling apparatus shall be in accord with the recommendations of I & A, Flue and Exhaust Gas Analyses PTC 19.10.

5.06 Method of Analysis. Apparatus and method of analysis to be employed are dependent upon the type of fuel burned and upon the purpose of the test. Design, construction and operation of the apparatus and preparation of the reagents shall be in accordance with I & A, Flue and Exhaust Gas Analyses PTC 19.10.

5.06.1 An analysis should be made to verify presence or absence of gaseous combustibles. If combustibles are found and cannot be eliminated by adjustment to the fuel burning equipment, the hydrogen and hydrocarbons shall be measured and the loss therefrom calculated as covered in Section 7.

5.06.2 For hydrogen and hydrocarbon analyses, it is necessary to obtain representative field samples of the gases for submission to a qualified laboratory. Refer to I & A, Flue and Exhaust Gas Analyses PTC 19.10.

5.07 Precautions. Proper steps shall be taken to prevent leakage to or from gas analyzing apparatus and sampling lines, to avoid contamination and exhaustion of reagents, to provide fresh reagents when needed, to keep manifolds clear of reagents, to avoid errors due to physical solubility of gases in reagents and confining liquids, to avoid personal injury by contact with reagents, to allow for burette error and drainage time, to avoid change of sample temperature during analysis, to keep apparatus clean, to minimize personal errors by employing careful operators who are given adequate information on common sources of error, to provide operators with adequate light and reasonable comfort, to verify results by checking against theoretical, and in all other ways, to assure that recorded data are correct and their degree of precision known. Sampling should be continuous when possible. Because all gases, especially SO_2 and CO_2, are soluble to some extent in water, the water in the levelling bottle shall be saturated with sample gas before taking any readings.

5.07.1 Detailed precautions given in I & A, Flue and Exhaust Gas Analyses PTC 19.10 shall be followed.

Flue Gas and Air Temperature Measurement

5.08 Outlet Flue Gas Temperature. Flue gas temperature measurement at the exit of the steam generator is required. This will be at locations 15, 14 or 12, Fig. 1 depending upon the equipment which comprises the steam generator. This may in certain instances be measured at other points such as the inlet to a waste heat boiler or at the inlet and discharge of air or gas recirculating fans.

5.08.1 Gas temperatures must be taken at the same sampling points as used for flue gas sampling, Par. 5.04, to minimize the effect of gas temperature stratification.

5.08.2 If a preliminary survey of flue gas flow, Par. 5.04, indicates severe stratification, it is recommended that the temperature measurements at individual locations in the duct cross section be weighted in proportion to the gas flow at the corresponding locations and an average of the weighted temperatures be used as representing the gas temperature at that cross section.

5.08.3 Choice of temperature measuring instruments depends upon the conditions of the individual case. The selection, design, construction, calibration, installation and operation of tempera-

ture measuring instruments shall be in accordance with I & A, Temperature Measurement PTC 19.3.

5.09 Air and Recirculated Flue Gas Temperature. The same general methods and the same precautions noted in Par. 5.08 shall apply to the determination of temperatures of primary air, secondary air, recirculated air or flue gas and temperature of air entering and leaving the air heater.

Flue Gas and Air Weight

5.10 Weight Determination. Flue gas quantity shall be determined by calculation from fuel analysis and flue gas composition. Calculation procedure for gas weight per heat unit of fuel is given in Par. 7.3.2.02. Similarly, air quantities shall be calculated as per Par. 7.2.8.1.

5.10.1 In some instances it is desirable to know flue gas or air quantities other than total for the unit, such as recirculated flue gas, primary air, secondary air, etc. These may be calculated by heat balances, by differences or may be measured if they cannot be calculated.

5.10.2 Methods of measurement available for flue gas and air quantity for testing purposes are covered in ASME publication Fluid Meters – Their Theory and Application. Where continual knowledge of such flows is required, flow nozzles, venturi or thin plate orifices can be installed following procedures outlined in I & A, Measurement of Quantity of Materials PTC 19.5, Chapter 4.

Refuse

5.11 Quantity Measurement. The heat loss method of this Code requires the determination of heat loss due to unburned combustible in the refuse. It is also necessary in the input-output method if the test is to be checked by a heat balance. From the viewpoint of testing, the most difficult part of this determination is the accurate measurement of all the refuse discharged or removed from the unit. In some installations it may be impractical or even impossible to collect and weigh all the refuse. When this is the case, it becomes necessary to estimate any undetermined amounts of refuse by volumetric measurement or a refuse balance difference. Care should be exercised to include all the refuse discharged or removed from the unit and to exclude any refuse which is returned to the unit for further combustion. In order to be sure that the refuse collected is in proper relation to the weight of ash in the coal burned, the collection must take into account the time required for the refuse to pass from the furnace to the point of discharge, as discussed in Par. 3.07. This may be especially important in stoker fired units.

5.11.1 The refuse collected at various points in the unit shall be weighed separately and preferably in the dry state, although any burning refuse must be quenched with water immediately upon its withdrawal from the unit. The moisture content of the refuse shall be determined by laboratory analysis. Flue dust collected at all points in the steam generating unit ahead of the samples taken from the gas stream, shall be collected, weighed, sampled and analyzed separately. The amount and combustible content of the fly ash carried in suspension by the flue gas shall be determined in accordance with Pars. 5.13 to 5.19, inclusive.

5.12 Sampling. Refuse sampling is subject to large errors and every precaution shall be taken to insure as representative a sample as possible.

5.12.1 Soot, siftings, cinders and dust separator refuse collected in hoppers shall each be reduced by successive quartering to obtain two 15 pound samples in each location. Where the total collection is less than 30 pounds for the duration of the test, the quantity shall be equally divided to constitute the two required samples. One sample shall be sent to the laboratory for analysis and the other sample shall be retained as a duplicate until final results of the tests have been reviewed and declared acceptable.

5.12.2 In the case of furnace bottom refuse either from a stoker fired or dry bottom pulverized fuel fired unit a gross sample of approximately 1000 pounds shall be taken in equal increments of approximately 50 pounds from each ton of refuse. Care shall be exercised to obtain proper proportions of coarse and fine refuse in each increment. If the total amount of furnace bottom refuse is less than 1000 pounds, then the entire amount of refuse shall constitute the gross sample. The gross sample shall be crushed and reduced to two 15 pound samples in accordance with instructions and Table I of ASTM Specification D 492 for coal sampling. One sample shall be sent to the labo-

ratory for analysis and the other shall be retained as a duplicate until final results have been reviewed and declared acceptable.

5.12.3 The reduction of the gross samples to laboratory size shall proceed as rapidly as possible to prevent undue loss of moisture by evaporation and the two laboratory size samples shall be placed and sealed in airtight containers.

5.13 Analysis. Refuse samples shall be analyzed for moisture, combustible content and heat value.

5.13.1 For moisture determination, the refuse shall be crushed, if necessary, in a jaw crusher to pass through a 4-mesh sieve, spread over suitable galvanized iron pans, and dried at a temperature in the range of 220 F to 230 F in an air drying oven until the weight loss per hour is not more than 0.1 per cent of the weight of the sample. Suitable pans and drying ovens are described in ASTM Specification D 271. Care shall be used, when drying samples of fine material such as refuse from soot hoppers and precipitators, to regulate the flow of air through the drying oven to a velocity which will not pick up and carry away any of the sample.

5.13.2 The heat value of the refuse shall be determined by bomb calorimeter, ignition loss method and/or by assuming that the combustible is carbon. In the calorimetric determination of the heat value of refuse, if the combustible is too low for ignition, it is necessary to add a measured quantity of combustible of known heat value to the refuse sample.

5.13.3 For high ash material the direct determination of heating value of refuse by the bomb calorimeter is difficult and subject to errors. A more accurate method is to determine the total hydrogen and carbon in the refuse and calculate the heating value. Provisions must be made to exclude hydrogen from water in the sample and carbon from inorganic carbonates.

5.13.4 The method used to determine the carbon and hydrogen is the combustion train as described in ASTM Standards on Coal and Coke D 271 with appropriate modifications in amount of sample and handling technique. Apparatus, reagents and preparations are described in ASTM D 278.

5.13.5 Procedure modifications are to weigh a sampling boat contained in a weighing bottle, then adding approximately 1.0 grams of sample and drying in a moisture oven at 105 C to a constant weight. Seal the sample and boat in the weighing bottle, weigh when cool and keep intact until introduced into the combustion train.

5.13.6 When the sample is treated as above the carbon and hydrogen calculated as described in ASTM D 278 will be on a dry basis, eliminating corrections for water hydrogen in the sample. Since the total carbon so determined includes carbon from inorganic carbonates in addition to combustible carbon, it is necessary to determine a correction. One of the methods described in ASTM D 1760 Carbon Dioxide in Coal can be used.

5.13.7 The calculated refuse heating value is equal to the sum of the products of weight fraction and high-heat value for combustible carbon and hydrogen contents in the refuse.

5.14 Dust Sampling and Analysis. The general principles of sampling apply to tests made to determine the dust analysis and concentration in flue gas as well as to occasional tests for fineness of coal and for properties of suspended materials in gaseous fuel to burners. Dust samples are obtained by inserting one or more sampling tubes into and facing the gas stream in question, drawing off a measured quantity of the gas at such a rate that the velocity of the gas entering the mouth of the sampling tube is the same as the velocity of the main body of gas at that point in the cross section of the duct and collecting all the dust carried by this quantity of gas.

5.14.1 All apparatus and test procedures shall be in accordance with the Test Codes for Dust Separating Apparatus PTC 21 and Determining Dust Concentration in a Gas Stream PTC 27.

5.15 Design of Dust Sampling Apparatus. The design of sampling apparatus shall be in accordance with the instructions of the Test Code for Dust Separating Apparatus PTC 21.

5.15.1 The volume of gas drawn through the sampling tube shall be measured by a displacement gas meter of known accuracy, by an orifice or flow nozzle, or by some other acceptable means such as a pitot tube suitably incorporated in the sampling tube.

5.15.2 Separation of dust from the gas sample shall be by suitable filters of ceramic or paper thimble or cloth bag type, by one of these in

conjunction with a cyclone separator or by other acceptable sample collecting apparatus.

5.15.3 It is usually necessary to draw the gas sample through the sampling tube, separator and metering apparatus. For this purpose, air, water and steam operated aspirators and motor driven pumps and blowers, such as employed in vacuum cleaners, are suitable. In general, use of the blower is limited to types of collecting sample apparatus having relatively low resistance.

5.15.4 In cases where normal temperature of the apparatus is below the dew point of the gas samples, precipitation of moisture shall be prevented by suitable insulation or by heating the apparatus.

5.16 Dust Sampling Points. A careful preliminary survey shall be made to show the variation in dust concentration over the cross section of the duct as a guide in determining the number and location of sampling points necessary to obtain the required accuracy. Points of sampling should be located in a long straight run of duct, preferably vertical rather than horizontal, shall be not more than three feet apart and a total of not less than four points shall be used. In round ducts, test points shall be located on two traverses along axes normal to each other, as described in the Test Code for Determining Dust Concentration in a Gas Stream PTC 27.

5.17 Dust Sampling Tubes. Since the number of sampling points necessary to attain the required accuracy will probably exceed the number of samplers it is practical to employ, the sampling tubes should be so designed that they can be moved to sample each required point.

5.18 Method of Determining Proper Rate of Gas Flow Through Dust Sampler. Proper sampling rates at each sampling point shall be determined by a pitot tube or its equivalent. Where duct velocities are determined by pitot tube and the gas at the sample metering device is at a temperature or pressure appreciably different from that in the duct, proper allowances shall be made. In some instances a traverse of the duct with a thermocouple is necessary.

5.19 Dust Sampling Precaution. Sampling should be continued throughout the duration of the run. Filters shall be changed when necessary, with the least possible loss of time. Correction shall be made for time lost while changing filters.

5.19.1 Sampling shall begin immediately after inserting the sampling tube in the duct. The stopping of sampling and the removal of the sampling tube shall likewise be as nearly simultaneous as possible.

5.19.2 When a sampling tube is moved from point to point to obtain an average, the duration of exposure shall be the same at all points and the sampling rate shall be regulated to correspond with the duct velocities at the individual points. The mouth of the sampling tube shall always point in the upstream direction.

5.19.3 Great care must be exercised to collect all the dust drawn into the sampling tube. This often requires that the piping between the sampling mouth and the dust separating device be cleaned with a weighed swab and the dust so collected accounted for. The sample and its container must be thoroughly dried before weighing.

5.19.4 Before use, filter bags, thimbles and other parts in which dust for the sample may collect shall be thoroughly dried and accurately weighed. This weight and that of any swabs or other cleaning media constitute a tare weight in the calculation.

5.20 Moisture in Combustion Air. The moisture carried by combustion air must be taken into consideration when calculating the efficiency by the heat loss method. This moisture may be determined with the aid of a sling-type psychrometer or similar device. From the dry- and wet-bulb thermometer readings taken from the psychrometer at the observed barometric pressure, the absolute or specific humidity (pounds of moisture per pound of dry air) can be determined either from the chart published in I & A, Part 18, Humidity Determinations, or from psychrometic tables published in the U. S. Weather Bureau Bulletin No. 235.

5.20.1 The dry and wet bulb temperatures may be determined at the atmospheric air inlet to the system. This is possible since the desired quantity is pounds of moisture per pound of dry air for combustion. Since the specific humidity does not change with heat addition unless there is moisture addition, the air moisture crossing the envelope, Fig. 1, is the same as that measured at the air inlet.

Radiation and Ashpit Losses

5.21 Surface Radiation and Convection. The radiation heat loss will be approximated by the use of the chart included in Section 7, Fig. 8. The measurement of the radiation heat loss on any installation, particularly a large one, requires an extensive installation of thermocouples over selected areas. See Appendix, Par. 9.5. Recent radiation tests on large installations showed that the value of radiation loss given by the reference curve is conservatively high.

5.22 Radiation Loss to the Ashpit. Part of the heat released in the furnace is transmitted to the ashpit by radiation and is lost as sensible heat in the ash discharged to the ashpit and in the ashpit water. In small boilers with dry ashpits which are not equipped with means for quenching the ash, a portion of this heat is lost through the walls of the ashpit. Since it is difficult and impractical to measure this loss for this type of boiler, it is not calculated as an individual loss but is included as a part of surface radiation and convection. Par. 5.21.

5.23 Wet Ashpit Losses-Evaporation and Heat to the Liquid. In boilers with dry ashpits provided with quenching pool ash hoppers and in continuous slag tap boilers provided with slag quenching tanks, the heat loss to the ashpit is manifested by a rise in quenching water temperature and by evaporation of a portion of the quenching water. Under these conditions, it is possible to determine this loss to the ashpit with a reasonable degree of accuracy by measuring very accurately the quantity and temperature of the water flowing to the ash hopper or quenching tank and the quantity and temperature of the overflow water. The quantity of water evaporated is equal to the difference between these quantities, corrected for the water displaced by the ash falling into the hopper or tank. It is important that the displaced quantity of water be carefully estimated.

5.23.1 The water level in the ash hopper or slag quenching tank shall be maintained as nearly constant as practicable. The level at the beginning and end of each test run shall be recorded and allowance shall be made in the calculations for the difference in volumes.

5.23.2 Stabilize water flows and temperatures between the time ashes are sluiced and the time the test run begins.

5.23.3 It is important to eliminate leakage of quenching water from the ash hopper or slag quenching tank in order to insure accurate test results. If leakage cannot be eliminated, then it must be measured and allowance made for it in the calculations.

5.23.4 Water flow to the ash hopper or quenching tank shall be measured by means of an orifice plate, flow nozzle or water meter. The gravity overflow shall be measured by means of weigh tanks, volumetric tanks or weir plate mounted in a weir tank provided with stilling baffles and a hook gage.

5.23.5 Although the quantity of quenching water evaporated is relatively small compared with the quantity of water flowing to the ash hopper or quenching tank, the heat loss due to evaporation of the quenching water is a relatively large part of the ashpit heat loss. For this reason, it is recommended that the device used to measure the flow of water to the ash hopper or quenching tank be calibrated with the same equipment used to measure the overflow to insure that the error in measurement of the difference between these two quantities will be a minimum.

5.23.6 The method of calculating the heat loss for those types of ashpits is detailed in Par. 7.3.2.11.

SECTION 6, MISCELLANEOUS INFORMATION

6.1 Power for Auxiliaries. For determining the energy consumption of the auxiliaries *inside the envelope*, Fig. 1, the information listed below is required.

6.1.1.1 Determination of energy consumption of steam auxiliary drives necessary for the operation of the steam generator requires measurement of steam flow quantities, and the initial and exhaust steam pressures, temperatures, and quality. Methods of measuring these are in general the same as those described in Output Measurement, Pars. 4.13 to 4.21.4, inclusive. Steam quantities may be determined by heat balance calculations on feedwater heaters, etc., the necessary corrections and precautions in regard to leakage, heat loss, etc., being observed.

6.1.1.2 Determination of energy consumption of electrically driven auxiliaries shall be made in accordance with the methods described in I & A, Part 6 on Electrical Measurements in Power Circuits PTC 19.6. Watthour meters are generally preferable to other types of instruments for this purpose.

6.1.2 In evaluating the heat equivalent of auxiliaries the equipment should be operated as near design conditions as possible.

6.2 Net Efficiency. As stated in Pars. 1.06 and 1.08, performance of steam generating units shall be based on the gross efficiency only. Net efficiency, while beyond the scope of this Code, is sometimes a matter of interest and therefore the following is included as an aid to those considering this facet of performance. Net efficiency is the output of the steam generator, which is the heat absorbed by the working fluid, divided by the total of all the heat in the fuel, plus credits, plus the heat equivalent of the auxiliaries *outside the envelope*, plus the heat equivalent of the driver losses of the auxiliaries *inside the envelope*. The following constitutes the usual auxiliaries outside the envelope, see Fig. 1, and therefore should be included in computing net efficiency:

Forced draft fans
Induced draft fans
Recirculating air fans
Soot blowers
Ash or flue dust handling systems (clinker grinders, conveyors, etc.)
Electric precipitators
Control drives
Fuel handling systems (prorate to steam generator being tested)
Fuel pumps (if central system, prorate to steam generator being tested)
Coal preparation systems (pulverized coal or cyclone fired storage or bin systems — prorate to steam generator being tested)
Stoker drives
Auxiliary boilers (prorate to steam generator being tested)
Cooling water (prorate to steam generator being tested)
Light and heat (prorate for area of plant occupied by steam generator being tested)

To the heat equivalent of the above listed auxiliaries *outside* the envelope, must be added the heat equivalent of the driver losses of the auxiliaries *inside* the envelope including motors, turbines, electric and hydraulic couplings and gears that may be associated with the following auxiliaries:

Pulverizers
Exhausters
Crushers
Boiler circulating pumps
Recirculating gas fans
Air heaters

6.2.1 Heat equivalent of all steam driven auxiliaries is:

Hourly steam flow × (Enthalpy in inlet steam − isentropic enthalpy of exhaust steam) = Btu per hr.

Where

Steam flow = metered flow in lb per hr.

Enthalpy of inlet steam is the enthalpy at inlet pressure and temperature or quality.

Isentropic enthalpy of exhaust steam is the enthalpy at exhaust pressure and initial entropy.

6.2.1.1 This computation will require metering of steam and determining inlet pressure, inlet steam temperature or moisture, and exhaust pressure. Steam quantities may be determined by heat balance calculations on the plant heat cycle if the arrangement of the cycle permits this.

6.2.1.2 Measurement of steam flow, temperature, pressure and moisture should follow procedures given in Pars. 4.17 to 4.21, inclusive.

6.2.2 Heat equivalent of all electrically driven auxiliaries will be:

$$\text{kilowatt input} \times 3413 = \text{Btu per hr}$$

6.2.2.1 The power input is preferably determined by watt or watthour meters, but where this is not possible, reliable ammeter, voltmeter and power factor readings may be used and heat equivalent for the usual 3 phase power is then:

$$\frac{\sqrt{3} \times \text{Volts} \times \text{Amperes} \times \text{Per cent Power factor}}{1000 \times 100} \times 3413$$

$$= \text{Btu per hr}$$

6.2.2.2 Electrical measurements should be made as specified in I & A Electrical Measurements in Power Circuits PTC 19.6.

6.2.3 When auxiliaries are a combination of steam and electrically driven equipment, the heat equivalent will be the sum of the heats calculated by Pars. 6.2.1 and 6.2.2, respectively.

6.3 Special Instructions for Testing a Waste Heat Boiler. Waste heat boiler testing technique differs from that employed with a steam generator to which the major energy is supplied in the form of fuel.

6.3.01 Input is the total of the sensible and latent heat contents of the entering gas stream, any radiation into the boiler and the chemical heat of combustion resulting from burning of supplementary fuel or residual combustible products in the entering gas. To this equivalent fuel energy input must be added any of the conventional heat credits listed on Fig. 2, which may include sensible heat of supplementary fuel and combustion air entering the boiler, etc.

6.3.02 Output takes the same form found in conventional steam generators, i.e., heat absorbed by the working fluid.

6.3.03 Determination of input and output quantities shall follow methods outlined in Section 4 wherever applicable.

6.3.04 Methods to be employed in determining or otherwise allowing for radiation heat input to the unit will depend upon individual conditions. The heat added from outside radiation may be estimated from the temperatures of heat source and absorbing surface and flat projected areas of radiating source and absorbing surfaces.

6.3.05 Determination of the heat content of the gas entering the boiler requires measurement of temperature and weight flow of gas, and analysis of the gas.

6.3.06 Gas temperature measurement at the boiler inlet requires special equipment and procedures. Because of the high temperatures usually encountered, probes must be water cooled. If inlet temperature measurements are taken at a location which permits the thermocouple to radiate to a surface at a lower temperature than the gas being measured, all measurements must be made with properly designed high temperature thermometry, see I & A, Temperature Measurement PTC 19.3.

6.3.07 Gas quantity entering may be determined by the following methods: (1) calculation from the amount of fuel burned in the process, analysis of this fuel and waste gas composition; (2) actual measurement of the gas quantity; (3) measurement of the gas quantity leaving the boiler, analysis of the gases entering and leaving the boiler and calculation of any supplementary combustion products. For method (1) fuel quantity and analysis shall be determined in accordance with Pars. 4.02 to 4.11, inclusive. Method (2) requires use of calibrated flow nozzles, orifices or water cooled pitot tube and temperature probes in accordance with I & A, PTC 19.3 and PTC 19.5. Method (3) minimizes problems arising from measurements in high temperature gas streams but still requires water cooled sampling probes at the boiler inlet to prevent reaction between probe metal and gas sample. Sampling shall be in accordance with Pars. 5.04 to 5.10, inclusive.

6.3.08 Heat content of entrained matter entering and leaving must be determined for calculation of total heat content of waste gas. Sampling of particulates shall be in accordance with Pars. 5.14 to 5.19, inclusive.

6.3.09 Losses will vary with types of input.

6.3.09.1 For boilers which do not involve combustion within the waste heat unit, heat losses consist of: (1) the difference between sensible heat content of the gas at the exit gas temperature and reference air temperature — usually ambient — (dry gas loss), see Par. 7.3.2.03;

(2) the difference between the latent heat content of the gas at the exit gas temperature and reference air temperature. (Loss due to moisture in the stack gas), see Par. 7.3.2.05; (3) radiation and convection loss may be obtained from ABMA radiation loss chart, see Fig. 8, by taking the radiation loss per cent and multiplying it by 100 times the gross heat input.

6.3.09.2 For boilers which include combustion within the unit, conventional steam generator losses, as defined in Section 5, should be accounted for and on a proportional basis added to the losses computed in the preceding paragraphs to constitute the units total losses. Basis for proportioning shall be a ratio of weight of all constituents entering into combustion to total gas weight, as discussed in Par. 5.10.

6.3.10 When determining the efficiency the duration of runs shall be not less than four hours.

SECTION 7, COMPUTATIONS

7.1 The following computation procedures are for determining the gross efficiency of a steam generating unit by both the input-output and the heat loss methods for the actual operating conditions of the tests. Where a comparison is to be made between test efficiency and a standard or guaranteed efficiency, adjustments should be made in computations for deviation of test conditions from the standard or guaranteed conditions for certain heat credits and heat losses. Each computation subject to adjustment is so noted in the following section, and the procedure for adjusting is as described under "Corrections to Standard or Guarantee Conditions." Pars. 7.4 to 7.6, inclusive.

Efficiency by Input-Output Method

7.2 $\eta_g = \dfrac{\text{Output}}{\text{Input}}$

Where

Output is defined as the heat absorbed by the working fluid

Input is defined as chemical heat in the fuel plus heat credits added to the working fluid, air, gas and other fluid circuits which cross the envelope boundary, see Fig. 1.

$$\eta_g = \left[\frac{W_{se31}\ (h_{s32} - h_{w24}) + W_{we25}\ (h_{s32} - h_{w25})}{H_f \times W_{fe} + B_e} + \frac{W_{se33}\ (h_{s34} - h_{s33}) + W_{we26}\ (h_{s34} - h_{w26}) + W_{we35}\ (h_{w35} - h_{w24})}{H_f \times W_{fe} + B_e} \right] \times 100$$

Note 1: The preceding equation applies to the more common single reheat usage. For multiple reheats, the heat absorbed in successive stages of reheat is additive in the numerator.

Note 2: Auxiliary steam usages are not indicated in the above equation, but wherever they occur, their heats are additive in the numerator.

Note 3: When testing steam generators which incorporate a circulating pump the following must be added to the outputs in the numerator of the equation:

$$W_{we48}\ (h_{w48} - h_{w47}) + (W_{we47} - W_{we48}) \times (h_{w24} - h_{w47})$$

The first group of terms correct for the heat removed by the "leak-off" water and the second group accounts for the heat required to bring the injected water to economizer inlet water temperature.

Where

η_g = Per cent = Gross efficiency.

7.2.1 $W_{se31} = \dfrac{\text{lb steam}}{\text{hr}}$ = Steam flow entering superheater.

7.2.2 $W_{se33} = \dfrac{\text{lb steam}}{\text{hr}}$ = Reheat steam flow.

7.2.3 h_{s32}, h_{s33}, $h_{s34} = \dfrac{\text{Btu}}{\text{lb steam}}$ = Enthalpy of steam at superheater outlet, reheater inlet and reheater outlet.

7.2.4 h_{w24}, h_{w25}, h_{w26}, h_{w35}, h_{w47}, $h_{w48} = \dfrac{\text{Btu}}{\text{lb water}}$ = Enthalpy of feedwater entering unit, enthalpy of superheater spray water, enthalpy of spray water, enthalpy of blowdown, enthalpy of injection water, and enthalpy of leak-off.

7.2.5 W_{we25}, W_{we26}, W_{we35}, W_{we47}, $W_{we48} = \dfrac{\text{lb water}}{\text{hr}}$ = Superheater spray water flow, reheat spray water flow, blowdown flow, injection flow, and leak-off flow.

7.2.6 $H_f = \frac{\text{Btu}}{\text{lb A.F. fuel}}$ = Heating value of fuel to be obtained by laboratory analysis and adjusted to an "as fired" basis from laboratory determination of moisture in fuel. For gaseous fuels, the use of continuous recording calorimeter is permitted, see ASTM D 1826.

7.2.6.1 Adjustment for moisture will be as follows:

$$H_f = H_{f'} \times \frac{100 - m_f}{100}$$

Where

$H_{f'} = \frac{\text{Btu}}{\text{lb fuel (dry basis)}}$ = Laboratory determination by fuel analysis on a dry basis.

m_f = Per cent moisture in fuel as determined by analysis of moisture sample.

7.2.6.2 When the heating value is determined at constant volume (see Pars. 4.05 and 4.08) it must be converted to a constant pressure value as follows:

$$H_f = H_{fp} = H_{fv} + \frac{\Delta\Psi R_u T}{778.2} = H_{fv} + \Delta\Psi \frac{1545 \times 537}{778.2}$$

$$H_f = H_{fv} + \Delta\Psi 1066 = H_{fv} + \frac{1066}{4.032} \text{ H} = H_{fv} + 264.4 \text{ H}$$

$H_{fp} = \frac{\text{Btu}}{\text{lb A.F. fuel}}$ = High-heat value of fuel at constant pressure.

$H_{fv} = \frac{\text{Btu}}{\text{lb A.F. fuel}}$ = High-heat value of fuel at constant volume.

$\Delta\Psi = \frac{\text{lb moles}}{\text{lb A.F. fuel}}$ = lb moles of oxygen removed in the reaction by the condensing water vapor formed.

$$\Delta\Psi = \frac{\text{H}}{2 \times 2.016} = \frac{\text{H}}{4.032}$$

$\text{H} = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of hydrogen exclusive of that in moisture per pound of "as fired" fuel from laboratory analysis.

$R_u = 1545 \frac{\text{ft-lb}}{\text{lb mole R}}$ = Universal Gas Constant.

T = 537 R = Standard Calorimeter Temperature.

778.2 ft-lb = 1 Btu = mechanical equivalent of heat.

See Appendix for complete derivation of above formula for conversion of high-heat value at constant volume as obtained with the bomb calorimeter to the high-heat value at constant pressure.

7.2.7 $W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = measured fuel rate.

If solid or liquid fuels are used the weight is determined by direct measurement. If gaseous fuel is used, the measured volume must be converted to a weight basis as follows:

7.2.7.1 $W_{fe} = Q_{fe} \times \gamma_f$

Where

$W_{fe} = \dfrac{\text{lb A.F. fuel}}{\text{hr}}$ = measured fuel rate.

$Q_{fe} = \dfrac{\text{cu ft}}{\text{hr}}$ = Quantity of gaseous fuel fired.

$\gamma_f = \dfrac{\text{lb}}{\text{cu ft}}$ = Fuel gas specific weight at the primary measuring element. This value may be obtained from standard American Gas Association tables, and corrected to 68 F.

7.2.8 $B_e = \dfrac{\text{Btu}}{\text{hr}}$ = Total heat credit and is defined as those amounts of heat added to the envelope of the steam generator other than the chemical heat in the fuel "as fired."

$$B_e = B_{Ae} + B_{ze} + B_{fe} + B_{xe} + B_{mAe}$$

7.2.8.1 $B_{Ae} = \dfrac{\text{Btu}}{\text{hr}}$ = Heat supplied by entering air from such sources as steam air heaters.

$$B_{Ae} = (W_{A'} - W_{A'_5}) \times W_{fe} \times c_{pA'}[t_{A7,A8} - t_{RA}] + W_{A'_5} \times W_{fe} \times c_{pA'}[t_{A'_5} - t_{RA}]$$

Where

$W_{A'} = \dfrac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of dry air per pound of "as fired" fuel

$$W_{A'} = \frac{(W_{G'N_2} - N)}{0.7685}$$

Where

$$W_{G'N_2} = \frac{\text{lb nitrogen in dry gas}}{\text{lb A.F. fuel}} = \frac{\text{lb dry gas}}{\text{lb A.F. fuel}} \times \frac{\text{lb nitrogen in dry gas}}{\text{lb dry gas}}$$

$$W_{G'N_2} = \frac{W_{G'} \times 28.02\ N_2}{44.01\ CO_2 + 32.00\ O_2 + 28.02\ N_2 + 28.01\ CO}$$

$W_{G'} = \dfrac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of dry gas per pound of "as fired" fuel

$$W_{G'} = \frac{44.01\ CO_2 + 32.00\ O_2 + 28.02\ N_2 + 28.01\ CO \times \left(C_b + \dfrac{12.01\ S}{32.07}\right)}{12.01\ (CO_2 + CO)}$$

$$W_{G'N_2} = \frac{28.02\ N_2}{12.01\ (CO_2 + CO)} \left(C_b + \frac{12.01\ S}{32.07}\right)$$

$$W_{A'} = \frac{W_{G'N_2} - N}{0.7685}$$

For complete fundamental derivation, see Appendix.

The preceding formula is based on molecular weights accurate to four significant figures, but it is not to be implied that the weight of dry air has this degree of accuracy. The four digit molecular weights are

used to hold errors from calculation procedures to a minimum. The values used are from the National Bureau of Standards Circular 564, dated 11/1/55.

CO_2, O_2 and CO = per cent by volume of dry flue gas. (Location 12, 14 or 15, Fig. 1.)

N_2 being determined by subtracting the total of CO_2, O_2 and CO from 100 per cent.

$$C_b = C - \frac{W_{d'p'} \times H_{d'p'}}{14500}$$

Where

$C_b = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of carbon burned per pound of "as fired" fuel.

$C = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds carbon in "as fired" fuel by laboratory analysis

$W_{d'p'} = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of total dry refuse per pound of "as fired" fuel, See Par. 7.3.2.01.

$H_{d'p'} = \frac{\text{Btu}}{\text{lb dry refuse}}$ = Heat value for total dry refuse from laboratory determination.

$14500 = \frac{\text{Btu}}{\text{lb}}$ = Heat value of 1 lb of carbon as it occurs in refuse.

$S = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds sulfur per pound of "as fired" fuel as determined for laboratory analysis.

$N = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of nitrogen per pound of "as fired" fuel.

For those who wish to know the theoretical air and excess air, the equations are given in the appendix.

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Fuel rate as determined by weighing procedures outlined in Section 4.

$c_{pA'}$ = Mean specific heat of dry air at inlet temperature, as obtained from curve sheet. See Fig. 3. It is determined from the instantaneous values over the range between inlet air temperature and the reference temperatures.

t_{A7} or t_{A8} = F = Inlet air temperature. If the unit is equipped with a steam or water coil air heater before the main air heater and it is supplied with heat from a source external to the unit being tested (as defined by Fig. 1), the inlet air temperature t_{A8} shall be measured in the air stream after this heater and in this case the heat added to the inlet air is a heat credit. If the coil above or recirculated hot air is being supplied by heat direct from the unit being tested, inlet air temperature t_{A7} shall be measured in the air stream ahead of the heater and there is no heat credit.

t_{RA} = F = Reference air temperature. This is the base temperature to which sensible heat losses and credits are compared for efficiency computations. When heat is added to the combustion air before the forced draft fan, corrections must be made to the measured temperature at location 7 on Fig. 1. Where adjustment is to be made for deviation from standard or guarantee conditions, see Par. 7.4.1.

7.2.8.2 $B_{ze} = \frac{\text{Btu}}{\text{hr}}$ = *Heat supplied by atomizing steam when the source is external to the unit being tested.*

$$B_{ze} = W_{ze} \times (h_{z42} - h_{Rv})$$

Where

$W_{ze} = \frac{\text{lb}}{\text{hr}}$ = Metered atomizing steam flow.

h_{z42} = Enthalpy of atomizing steam at pressure and temperature at metering point.

h_{Rv} = Enthalpy of saturated vapor at reference temperature.

7.2.8.3 $B_{fe} = \frac{\text{Btu}}{\text{hr}}$ = *Heat supplied by sensible heat in fuel.*

$$B_{fe} = W_{fe} \times c_{pf} (t_{f1,3,4} - t_{RA})$$

Where

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate

$c_{pf} = \frac{\text{Btu}}{\text{lb F}}$ = Mean specific heat of fuel. Use 0.3 Btu/lb/F for coal. See Fig. 4 for fuel oil. See Fig. 5 for gas. It is determined from the instantaneous values over the range between inlet fuel temperature and the reference temperature.

If liquid fuel is heated by a source external to the unit being tested, the inlet temperature shall be measured after this heater, but if heated directly from the unit being tested temperature shall be measured before the heater.

t_{f1}, t_{f3}, t_{f4} = F = Fuel inlet temperature.

t_{RA} = Reference air temperature.

7.2.8.4 $B_{xe} = \frac{\text{Btu}}{\text{hr}}$ = *Heat supplied by auxiliary drives within the envelope.*

$$B_{xe} = W_{sxe} (h_{sx} - h_{ix}) \eta_x$$

Where

$W_{sxe} = \frac{\text{lb}}{\text{hr}}$ = Steam flow rate.

$h_{sx} = \frac{\text{Btu}}{\text{lb}}$ = Enthalpy of the steam supplied to drive the auxiliaries.

$h_{ix} = \frac{\text{Btu}}{\text{lb}}$ = Enthalpy at the exhaust pressure and the initial entropy of steam supplied to drive the auxiliaries.

η_x = Over-all drive efficiency — includes turbine and gear efficiency.

For electric auxiliaries the heat supplied is:

B_{xe} = 3413 (kwh) η_x

η_x = Over-all drive efficiency — includes such items as motor efficiency, electric and hydraulic coupling efficiency and gear efficiency.

7.2.8.5 $B_{mAe} = \frac{\text{Btu}}{\text{hr}}$ = *Heat supplied from the moisture entering with the inlet air.*

$$B_{mAe} = W_{mA'} \times W_{A'e} \times c_{ps} \times (t_{A7}, t_{A8} - t_{RA})$$

Where

$W_{mA'} = \frac{\text{lb}}{\text{lb dry air}}$ = Pounds of water vapor per pound of dry air. Refer to Par. 5.20.

$W_{A'e} = W_{A'} \times W_{fe}$

Where

$W_{A'e} = \frac{\text{lb}}{\text{hr}}$ = Pounds of dry air supplied per hour.

$W_{A'} = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of dry air supplied per pound of "as fired" fuel. Refer to Par. 7.2.8.1.

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate.

$c_{ps} = \frac{\text{Btu}}{\text{lb F}}$ = Mean specific heat of steam from curve on Fig. 6. It is determined from the instantaneous values over the range between inlet steam temperature and reference temperature.

t_{A7} or t_{A8} = F = Inlet air temperature.

t_{RA} = F = Reference air temperature.

7.2.9 The foregoing heat credits are to be summarized into total heat credits and used as the value of B_e in the equation in Par. 7.2 for solving for gross efficiency by the input-output method.

Efficiency by Heat Loss Method

7.3

$$\eta_g = 100 - \frac{L}{H_f + B} \times 100$$

Derivation of this formula is as follows:

$$\eta_g = \frac{\text{Output}}{\text{Input}} \times 100$$

Where

η_g = Per cent = Gross efficiency

Output = Input − L as defined in Par. 1.04.4.

Input = $H_f + B$ as defined in Par. 1.04.3.

Then

$$\eta_g = \frac{\text{Input} - L}{H_f + B} = \frac{(H_f + B) - L}{H_f + B} = 1 - \frac{L}{H_f + B}$$

Converting to per cent:

$$\eta_g = 100 - \frac{L}{H_f + B} \times 100$$

Where

7.3.1

η_g = Per cent = Gross efficiency

7.3.2 $L = \dfrac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Total heat loss from the steam generator.

$$L = L^*_{UC} + L_{C'} + L_{mf} + L_A + L_{mA} + L^*_z + L_{CO} + L_{UH} + L_{UHC} + L_\beta + L^*_{\boxed{P}} + L^*_d + L^*_r + L^*_w$$

*A fuel rate is used in the calculation of these losses.

7.3.2.01

$L_{UC} = \dfrac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = *Heat loss due to unburned carbon in total dry refuse.*

$$L_{UC} = W_{d'p'} \times H_{d'p'}$$

Where

$$W_{d'p'} = \frac{W_{d'p'e}}{W_{fe}}$$

Where

$W_{d'p'} = \dfrac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of total dry refuse per pound of "as fired" fuel.

Where refuse rate at various collection points, such as ashpit, dust collector and boiler hoppers is not actually determined it may be estimated. See Par. 3.01.14.

$W_{d'p'e} = \dfrac{\text{lb}}{\text{hr}}$ = Pounds of total dry refuse rate.

$W_{fe} = \dfrac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate.

If fuel rate is not measured, the expected rate for the test may be used, and considered sufficiently accurate for this calculation. Iteration will be required for more accurate results.

$H_{d'p'} = \dfrac{\text{Btu}}{\text{lb dry refuse}}$ = Laboratory determination of per cent combustible × 14,500 Btu/lb

or

$Hd'p' = \dfrac{\text{Btu}}{\text{lb dry refuse}}$ = Laboratory determination of heating value.

If it is possible and desirable to measure the refuse collection rate at all collection points, then the following calculation procedure will be used to determine unburned carbon loss.

$$L_{UC} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}} = a + b + c + d + e$$

(a) Btu/lb in ashpit $= \dfrac{\text{lb dry refuse in ashpit}}{\text{lb A.F. fuel}} \times \dfrac{\text{Btu}}{\text{lb ashpit refuse}}$

(b) Btu/lb in boiler hopper $= \dfrac{\text{lb dry refuse in boiler hopper}}{\text{lb A.F. fuel}} \times \dfrac{\text{Btu}}{\text{lb boiler hopper refuse}}$

(c) Btu/lb in econ. hopper $= \dfrac{\text{lb dry refuse in economizer hopper}}{\text{lb A.F. fuel}} \times \dfrac{\text{Btu}}{\text{lb econ. hopper refuse}}$

(d) Btu/lb in air heater hopper $= \dfrac{\text{lb dry refuse in air heater hopper}}{\text{lb A.F. fuel}} \times \dfrac{\text{Btu}}{\text{lb air heater hopper refuse}}$

(e) Btu/lb in dust collector hopper $= \dfrac{\text{lb dry refuse in dust collector hopper}}{\text{lb A.F. fuel}} \times \dfrac{\text{Btu}}{\text{lb dust collector refuse}}$

If the flue dust is sampled prior to all collection points, with the exception of the ashpit, and all parties agree ashpit combustible is negligible, flue dust rate may be estimated or determined by dust concentration measurements. Then the loss due to unburned combustible will become:

$$L_{UCd} = \frac{\text{Btu}}{\text{lb A.F. fuel}} = \textit{Heat loss due to unburned carbon in flue dust.}$$

$$L_{UCd} = W_{d'} \times H_{d'}$$

Where

$$W_{d'} = \frac{\text{lb}}{\text{lb A.F. fuel}} = \text{Pounds of dry flue dust per pound of "as fired" fuel.}$$

$$\dot{H}_{d'} = \frac{\text{Btu}}{\text{lb of dust}} = \text{Heat value of flue dust.}$$

7.3.2.02

$$L_{G'} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}} = \textit{Heat loss due to heat in dry flue gas.}$$

$$L_{G'} = W_{G'} \times c_{pG'} \, (t_G - t_{RA})$$

Where

$$W_{G'} = \frac{\text{lb}}{\text{lb A.F. fuel}} = \text{Pounds of dry gas per pound of "as fired" fuel.}$$

$$W_{G'} = \frac{44.01\ CO_2 + 32.00\ O_2 + 28.02\ N_2 + 28.01\ CO}{12.01\ (CO_2 + CO)} \times C_b + \left[\frac{12.01\ S}{32.07}\right]$$

The preceding formula is based on molecular weights accurate to four significant figures, but it is not to be implied that the dry gas loss has this degree of accuracy. The four digit molecular weights are used to hold errors from calculation procedures to a minimum. The values used are from the National Bureau of Standards Circular 564, dated 11/1/55.

CO_2, O_2, and CO = per cent by volume of dry flue gas (location 12, 14 or 15, Fig. 1)

N_2 being determined by subtracting the total of CO_2, O_2 and CO from 100 per cent.

$$C_b = C - \frac{W_{d'p'} \times H_{d'p'}}{14500}$$

Where

$$C_b = \frac{\text{lb}}{\text{lb A.F. fuel}} = \text{Pounds of carbon burned per pound of "as fired" fuel.}$$

$$C = \frac{\text{lb}}{\text{lb A.F. fuel}} = \text{Pounds of carbon in "as fired" fuel by laboratory analysis.}$$

$$W_{d'p'} = \frac{\text{lb}}{\text{lb A.F. fuel}} = \text{Pounds of total dry refuse per pound of "as fired" fuel. See Par. 7.3.2.01}$$

$$H_{d'p'} = \frac{\text{Btu}}{\text{lb dry refuse}} = \text{Heat value for total dry refuse from laboratory determination.}$$

$$14500 = \frac{\text{Btu}}{\text{lb}} = \text{Heat value of 1 lb of carbon as it occurs in refuse.}$$

$S = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds sulfur per pound of "as fired" fuel as determined by laboratory analysis.

$c_{pG'} = \frac{\text{Btu}}{\text{lb F}}$ = Mean specific heat of the dry flue gas as obtained from curves on Fig. 7. It is determined from the instantaneous values over the range between gas temperature leaving the unit and the reference temperature.

t_G = Gas temperature leaving the unit, such as t_{G12}, t_{G14} or t_{G15}. If this temperature is to be corrected because of deviation from standard or guarantee air heater inlet air temperature see Par. 7.5.2.

t_{RA} = F = Reference air temperature. If this temperature is to be corrected because of deviation from standard or guarantee inlet air temperature see Par. 7.4.1.

7.3.2.03

$L_{mf} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to moisture in the "as fired" fuel.

$$L_{mf} = m_f (h_{12,14,15} - h_{Rw})$$

Where

$m_f = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds moisture per lb of "as fired" fuel by laboratory analysis.

$h_{12,14,15}$ = Enthalpy of vapor at partial pressure, and exit gas temperature $t_{G12,14,15}$ to be determined from steam tables.

$$P_{mG} = \frac{P_A}{1 + \frac{100 \times 1.5\ C_b}{m_G\ (CO_2 + CO)}}$$

Where

$P_{mG} = \frac{\text{lb}}{\text{sq in. abs}}$ = Partial pressure of the moisture in the flue gas.

The above formula is a rigorous treatment. For practical use, P_{mG} approximates one psia for the partial pressure existing at the steam generator exit.

$P_A = \frac{\text{lb}}{\text{sq in. abs}}$ = Atmospheric pressure

$C_b = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds carbon burned per lb A.F. fuel

$$m_G = 8.936\ H + (W_{mA'})\ (W_{A'}) + m_f + W_z + m_p$$

Where

$m_G = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of moisture in the flue gas per pound of "as fired" fuel.

8.936 = 8.936 pounds of water produced from burning one pound of hydrogen.

$H = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of hydrogen exclusive of that in moisture from an "as fired" fuel by laboratory analysis.

$W_{mA'} = \frac{\text{lb}}{\text{lb dry air}}$ = Pounds of moisture per pound of dry air at boiler inlet.

$W_{A'} = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of dry air per pound of "as fired" fuel.

$m_f = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of moisture per pound of "as fired" fuel.

$W_z = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of atomizing steam per pound of "as fired" fuel.

$m_p = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of moisture evaporated in ashpit per pound of "as fired" fuel.

CO_2, CO = per cent by volume of dry flue gas.

h_{Rw} = Enthalpy of saturated liquid at t_{RA} is used for solid and liquid fuels. Where moisture loss is to be adjusted for deviation from standard or guarantee conditions see Par. 7.5.4.

7.3.2.04

$L_H = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = *Heat loss due to moisture from burning of hydrogen.*

$L_H = 8.936 \times H\ (h_{12,14,15} - h_{Rw})$

Where

8.936 = 8.936 pounds of water produced from burning one pound of hydrogen.

$H = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of hydrogen exclusive of that in moisture in "as fired" fuel by laboratory analysis.

Remaining items will be identical with Par. 7.3.2.03. Where hydrogen loss is to be adjusted for deviation from standard or guaranteed conditions see Par. 7.5.4.

7.3.2.05

$L_{mA} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = *Heat loss due to moisture in the air.*

$L_{mA} = W_{mA'} \times W_{A'}\ [h_{12,14,15} - h_{Rv}]$

Where

$W_{mA'} = \frac{\text{lb}}{\text{lb dry air}}$ = Pounds of water vapor per pound of dry air obtained from Par. 5.20.

$W_{A'} = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of dry air supplied per lb of "as fired" fuel. Refer to Par. 7.2.8.1.

$h_{12,14,15}$ will be identical with Par. 7.3.2.03.

$h_{Rv} = \frac{\text{Btu}}{\text{lb } H_2O}$ = Enthalpy of the saturated vapor at t_{RA}. Refer to Par. 7.2.8.1

7.3.2.06

$L_z = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = *Heat loss due to heat in atomizing steam.*

$L_z = \frac{W_{ze}}{W_{fe}}(h_{12,14,15} - h_{Rv})$

Where

$W_{ze} = \frac{\text{lb}}{\text{hr}}$ = Pounds of metered or estimated atomizing steam as agreed to by all parties.

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate as in Par. 7.3.2.01.

$h_{12,14,15} = \frac{\text{Btu}}{\text{lb steam}}$ will be identical with Par. 7.3.2.03.

$h_{Rv} = \frac{\text{Btu}}{\text{lb } H_2O}$ = Enthalpy of saturated vapor at reference temperature at t_{RA}. Refer to Par. 7.2.8.1.

7.3.2.07

$L_{CO} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = *Heat loss due to formation of carbon monoxide.*

Where it is established that CO is present and cannot be eliminated by operating adjustments:

$$L_{CO} = \frac{CO}{CO_2 + CO} \times 10160 \times C_b$$

Where

CO and CO_2 per cent by volume of flue gas.

10160 = Btu generated burning 1 lb of carbon in CO to CO_2 and represents the difference between the burning carbon as it occurs in fuel to CO_2 (14540 Btu), and burning carbon as it occurs in fuel to CO (4380 Btu); that is 14540 − 4380 = 10160 Btu (Fuels & Combustion Hand-Book — Johnson & Auth, published by McGraw-Hill Book Company)

$C_b = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of carbon burned per lb of "as fired" fuel.

7.3.2.08

$L_{UH} = \frac{\text{Btu Loss}}{\text{lb A.F. fuel}}$ = *Heat loss due to unburned hydrogen.*

Where it is established that unburned hydrogen is present and cannot be eliminated by operating adjustments:

$$L_{UH} = \frac{\frac{H_2 \text{ (cu ft)}}{\text{cu ft dry gas}} \times W_{G'} \times 318.9}{\text{flue gas specific weight}}$$

Where

$\frac{H_2 \text{ (cu ft)}}{\text{cu ft dry gas}}$ = Laboratory determination of H_2 content of flue gas in Par. 5.06.

$W_{G'} = \frac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of dry gas per lb of "as fired" fuel as determined in Par. 7.3.2.02.

318.9 = Btu/cu ft of hydrogen at 14.7 psia and 68 F.

Flue gas specific weight at 68 F and 14.7 psia

$$= 0.0401 \left[\frac{CO_2}{35.11} + \frac{O_2}{48.28} + \frac{CO}{55.16} + \frac{N_2}{55.14} + \frac{SO_2}{24.12} + \frac{H_2}{766.36} + \frac{\frac{HC}{1545}}{M_{HC}} \right]$$

Where

CO_2, O_2, CO, etc. = Per cent = Per cent by volume constituents as determined by laboratory analysis of flue gas.

M_{HC} = Molecular weight of hydrocarbon in flue gas.

For derivation of flue gas specific weight, see Appendix.

7.3.2.09

$$L_{UHC} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}} = \textit{Heat loss due to unburned hydrocarbons.}$$

Where it is established that unburned hydrocarbons are present and cannot be eliminated by operating adjustments:

$$L_{UHC} = \frac{\dfrac{\text{UHC (cu ft)}}{\text{cu ft dry gas}} \times W_{G'} \times K_{UHC}}{100 \times \text{flue gas specific weight}}$$

Where

$\dfrac{\text{UHC (cu ft)}}{\text{cu ft dry gas}}$ = Laboratory determination of flue gas constituents as in Par. 5.06.

$W_{G'} = \dfrac{\text{lb}}{\text{lb A.F. fuel}}$ = Pounds of dry gas per lb of "as fired" fuel, as determined in Par. 7.3.2.02.

K_{UHC} = Btu/cu ft of unburned hydrocarbons as determined by laboratory analysis

Flue gas specific weight at 68 F and 14.7 psia determination in Par. 7.3.2.08.

7.3.2.10

L_{β} = *Loss due to surface radiation and convection.*

This loss may be obtained from ABMA radiation loss chart, see Fig. 8 and correction for air velocities, see Fig. 9 by taking the radiation loss per cent and multiplying it by the chemical heat in one pound of "as fired" fuel (H_f).

7.3.2.11

$$L_{[P]} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}} = \textit{Heat loss due to radiation to ashpit, sensible heat in slag, and if applicable the latent heat of fusion of slag.}$$

Where measured by procedures outlined in Pars. 5.22 and 5.23 will be:

$L_{[P]}$ = Heat loss to increasing temperature of pit water + heat loss to evaporation of pit water + sensible heat loss in the refuse as it leaves the pit.

$$\text{Heat loss to increasing temperature of pit water} = \frac{W_{we38} \times (t_{w39} - t_{w38})}{W_{fe}}$$

Where

$W_{we38} = \dfrac{\text{lb}}{\text{hr}}$ = Pounds of water per hour metered to pit.

t_{w39} = F = Water temperature leaving pit.

t_{w38} = F = Water temperature entering pit.

$W_{fe} = \dfrac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate as in Par. 7.3.2.01.

Heat loss to evaporation of pit water

$$= \left[W_{we38} + \left(W_{fe} \times \frac{p}{100} \times \frac{\text{specific weight of water}}{\text{specific weight of refuse}} \right)^{*} - W_{we39} \right] \times \left[\frac{h_{v12,14,15} - h_{w39}}{W_{fe}} \right]$$

Where

$W_{we38} = \frac{\text{lb}}{\text{hr}}$ = Pounds of water per hour metered to pit.

$W_{we39} = \frac{\text{lb}}{\text{hr}}$ = Pounds of water per hour metered from pit.

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate as in Par. 7.3.2.01.

p = pit refuse = in this case expressed as per cent of "as fired" fuel to pit.

Specific weight of water = lb/cu ft at t_{w39}.

Specific weight of refuse = lb/cu ft pit refuse by actual dry weight or as agreed to by participating parties.

$h_{v12,14,15}$ = Enthalpy of vapor as in Par. 7.3.2.03.

h_{w39} = Enthalpy of outlet water.

Heat loss due to the sensible heat in the refuse as it leaves

the pit $= C_{pp} \frac{W_{pe}}{W_{fe}} (t_{w39} - t_{RA})$

Where

$C_{pp} = \frac{\text{Btu}}{\text{lb F}}$ = Specific heat of wet refuse.

$W_{pe} = \frac{\text{lb}}{\text{hr}}$ = Pounds of wet refuse per hour.

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate as in Par. 7.3.2.01

t_{w39} = F = Water temperature leaving the pit

t_{RA} = F = Reference temperature as in Par. 7.2.8.1

Where refuse is removed in the dry state from the pit this loss may be measured as follows:

$L_{p'} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to sensible heat in the dry ashpit refuse.

$$L_{p'} = \frac{c_{pp'} (t_{p'37} - t_{RA}) \times W_{p'e}}{W_{fe}}$$

Where

$c_{pp'} = \frac{\text{Btu}}{\text{lb F}}$ = Specific heat of dry ashpit refuse at average refuse temperature. Use 0.25.

$t_{p'37}$ = F = Temperature of ashpit refuse as indicated in Fig. 1.

*The value within the parentheses may be determined from comparison of clean-pit and ash laden-pit water fill volumes, or an estimate of total ash volume in the pit and displacement measurements on sample batches of pit refuse.

t_{RA} = Reference air temperature as in Par. 7.2.8.1.

$W_{p'e} = \frac{\text{lb}}{\text{hr}}$ = Weighed or estimated dry ashpit refuse leaving pit.

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate as given in Par. 7.3.2.01.

7.3.2.12

$L_{d'} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = *Heat loss due to sensible heat in flue dust.*

$$L_{d'} = \frac{c_{d'}\ (t_{G12,14,15} - t_{RA}) \times W_{d'e}}{W_{fe}}$$

Where

$c_{d'} = \frac{\text{Btu}}{\text{lb F}}$ = Specific heat of flue dust at average flue dust temperature. Use 0.20.

$t_{G12,14,15}$ = F = Temperature of flue gas at each collection point as indicated in Fig. 1.

t_{RA} = F = Reference air temperature as in Par. 7.2.8.1.

$W_{d'e} = \frac{\text{lb}}{\text{hr}}$ = Weighed or estimated dust at each collection point.

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate as given in Par. 7.3.2.01

7.3.2.13

$L_r = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = *Heat loss due to heat in pulverizer rejects.*

$$L_r = \frac{W_{re} \times H_r}{W_{fe}}$$

Where

$W_{re} = \frac{\text{lb}}{\text{hr}}$ = Pounds of pulverizer rejects, preferably weighed.

$H_r = \frac{\text{Btu}}{\text{lb}}$ = Heating value of rejects from laboratory analysis of representative sample.

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate as given in Par. 7.3.2.01.

7.3.2.14

$L_w = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = *Heat loss due to heat pick-up by cooling water entering envelope* (Fig. 1).

$$L_w = \frac{W_{we}\ (t_{w\,\text{outlet}} - t_{w\,\text{inlet}})}{W_{fe}}$$

Where

$W_{we} = \frac{\text{lb}}{\text{hr}}$ = Pounds of cooling water flow.

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate as given in Par. 7.3.2.01.

7.3.2.15 *Summarizing Losses.*

$$L = L_{UC} + L_{G'} + L_{mf} + L_H + L_{mA} + L_z + L_{CO} + L_{UH} + L_{UHC} + L_\beta + L_{[P]} + L_d + L_r + L_w$$

Where

$L = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Total heat losses. Par. 7.3.2.

$L_{UC} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to unburned carbon in refuse. Par. 7.3.2.01

$L_{G'} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to heat in dry flue gas. Par. 7.3.2.02.

$L_{mf} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to moisture in the "as fired" fuel. Par. 7.3.2.03.

$L_H = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to moisture from burning of hydrogen. Par. 7.3.2.04.

$L_{mA} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to moisture in the air. Par. 7.3.2.05.

$L_z = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to heat in atomizing steam. Par. 7.3.2.06.

$L_{CO} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to formation of carbon monoxide. Par. 7.3.2.07

$L_{UH} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to unburned hydrogen. Par. 7.3.2.08.

$L_{UHC} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to unburned hydrocarbons. Par. 7.3.2.09.

$L_\beta = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to surface radiation and convection. Par. 7.3.2.10.

$L_{[P]} = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to rediation to ashpit, sensible heat in slag and, if applicable, latent heat of fusion of slag. Par. 7.3.2.11.

$L_d = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to sensible heat in flue dust. Par. 7.3.2.12.

$L_r = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to heat in pulverizer rejects. Par. 7.3.2.13.

$L_w = \frac{\text{Btu loss}}{\text{lb A.F. fuel}}$ = Heat loss due to heat pickup by cooling water entering envelope, Fig. 1, Par. 7.3.2.14.

7.3.3

$H_f = \frac{\text{Btu}}{\text{lb A.F. fuel}}$ = Chemical heat in fuel to be obtained as in Par. 7.2.6.

7.3.4

$$B = \frac{\text{Btu credit}}{\text{lb A.F. fuel}} = \text{Total heat credits per pound of "as fired" fuel added to the steam generator in the form of sensible heat.}$$

$$B = \frac{B_{Ae} + B_{ze} + B_{fe} + B_{xe} + B_{mAe}}{W_{fe}}$$

Where

$B_{Ae} = \frac{\text{Btu credit}}{\text{hr}}$ = Heat credit supplied by entering air. Par. 7.2.8.1

$B_{ze} = \frac{\text{Btu credit}}{\text{hr}}$ = Heat credit supplied by atomizing steam. Par. 7.2.8.2

$B_{fe} = \frac{\text{Btu credit}}{\text{hr}}$ = Heat credit supplied by sensible heat in fuel. Par. 7.2.8.3

$B_{xe} = \frac{\text{Btu credit}}{\text{hr}}$ = Heat credit supplied by auxiliary drives. Par. 7.2.8.4.

$B_{mAe} = \frac{\text{Btu credit}}{\text{hr}}$ = Heat credit supplied from the moisture entering with the inlet air. Par. 7.2.8.5.

$W_{fe} = \frac{\text{lb A.F. fuel}}{\text{hr}}$ = Measured fuel rate as given in Par. 7.3.2.01.

For a more accurate calculation of gross steam generator efficiency, the gross efficiency obtained from the initial calculation can be used as the basis for determining a refined fuel rate. When this value is substituted in formulas for determining heat losses and credits, a more accurate calculated gross efficiency is obtained.

Corrections to Standard or Guarantee Conditions

7.4 Corrections to Heat Credits.

7.4.1 Corrections to the heat credits, "heat supplied by entering air," and "heat supplied by sensible heat in fuel" for changes from test reference air temperature (see Par. 7.2.8.1) to a standard or guaranteed air inlet temperature are made by substituting the standard or guaranteed temperature for the test reference temperature in the heat credit formulas.

7.4.2 Corrections to the heat credits, "heat supplied by atomizing steam" and "heat supplied by moisture in entering air" for changes from test reference air temperature to a standard or guaranteed temperature air inlet temperature are made by substituting the enthalpy corresponding to the standard or guaranteed temperature for the enthalpy corresponding to the test reference temperature in the heat credit formulas.

7.5 Corrections to Heat Losses.

7.5.1 Corrections to heat losses, besides including a correction for changes from the test reference air temperature to standard or guaranteed air inlet temperature as in the treatment of heat credit corrections, must also include, when an air heater is used, a correction for the change in gas exit temperature result-

ing from the above change in air inlet temperature. The corrected gas outlet temperature is given in the Test Code for Air Heaters PTC 4.3 and uses the following formula:

$$t_{G15\delta} = \frac{t_{A8D}\ (t_{G14} - t_{G15}) + t_{G14}\ (t_{G15} - t_{A8})}{(t_{G14} - t_{A8})}$$

Where

$t_{G15\delta}$ = F = corrected air heater exit gas temperature.

t_{A8D} = F = Standard or guaranteed air heater inlet air temperature.

t_{G14} = F = air heater inlet gas test temperature.

t_{G15} = F = air heater exit gas test temperature.

t_{A8} = F = air heater inlet air test temperature.

A further minor correction caused by leakage differences between test and standard or guaranteed temperatures is being developed for the Test Code for Air Heaters PFC 4.3. When this later code is issued, this further correction is to be considered a part of PFC 4.1.

7.5.2 Corrections to the heat losses, "Dry gas loss" and "Heat loss due to sensible heat in the flue dust" for changes from test reference air temperature to a standard or guaranteed air inlet temperature are made by substituting the standard or guaranteed temperature for the test reference air temperature and also by substituting the corrected gas exit temperature for the test gas exit temperature in the heat loss formulas.

7.5.3 Corrections to the heat losses, "Heat loss due to moisture in fuel," "Heat loss due to moisture in air" and "Heat loss due to atomizing steam," for changes from the test reference air temperature to a standard or guaranteed air inlet temperature are made by substituting the appropriate enthalpy corresponding to the standard or guaranteed air inlet temperature for the enthalpy corresponding to the test reference air temperature and also by substituting the enthalpy corresponding to the corrected gas exit temperature for the enthalpy corresponding to the test gas exit temperature, in the heat loss formulas. The "appropriate" inlet enthalpy referred to above relates to the state of the entering moisture (liquid or vapor).

7.5.4 Corrections to the heat losses, "Heat loss due to moisture in fuel" and "Heat loss due to hydrogen in fuel" for changes of moisture and hydrogen content from the test fuel to the fuel used for the standard or guaranteed computations, are made by substituting the weight of moisture or hydrogen per pound of fuel in the standard or guaranteed fuel for the weight of moisture or hydrogen per pound of fuel, of the test fuel, in the heat loss formulas.

7.5.5 Corrections to the heat loss "Loss due to moisture in air" for changes of moisture content from the test air to the air used for standard or guaranteed computations, are made by substituting the weight of moisture in the standard or guaranteed air for the weight of the moisture in the test air, in the heat loss formula. The magnitude of this correction in most cases will be negligible.

7.5.6 Other heat losses listed in the computations are not considered in these correction paragraphs either because they do not apply or the magnitude of the correction is usually insignificant.

7.6 The corrected steam generator efficiency resulting from the preceding adjustments of credits and losses to standard or guarantee conditions can then be compared with the standard or guarantee conditions, respectively.

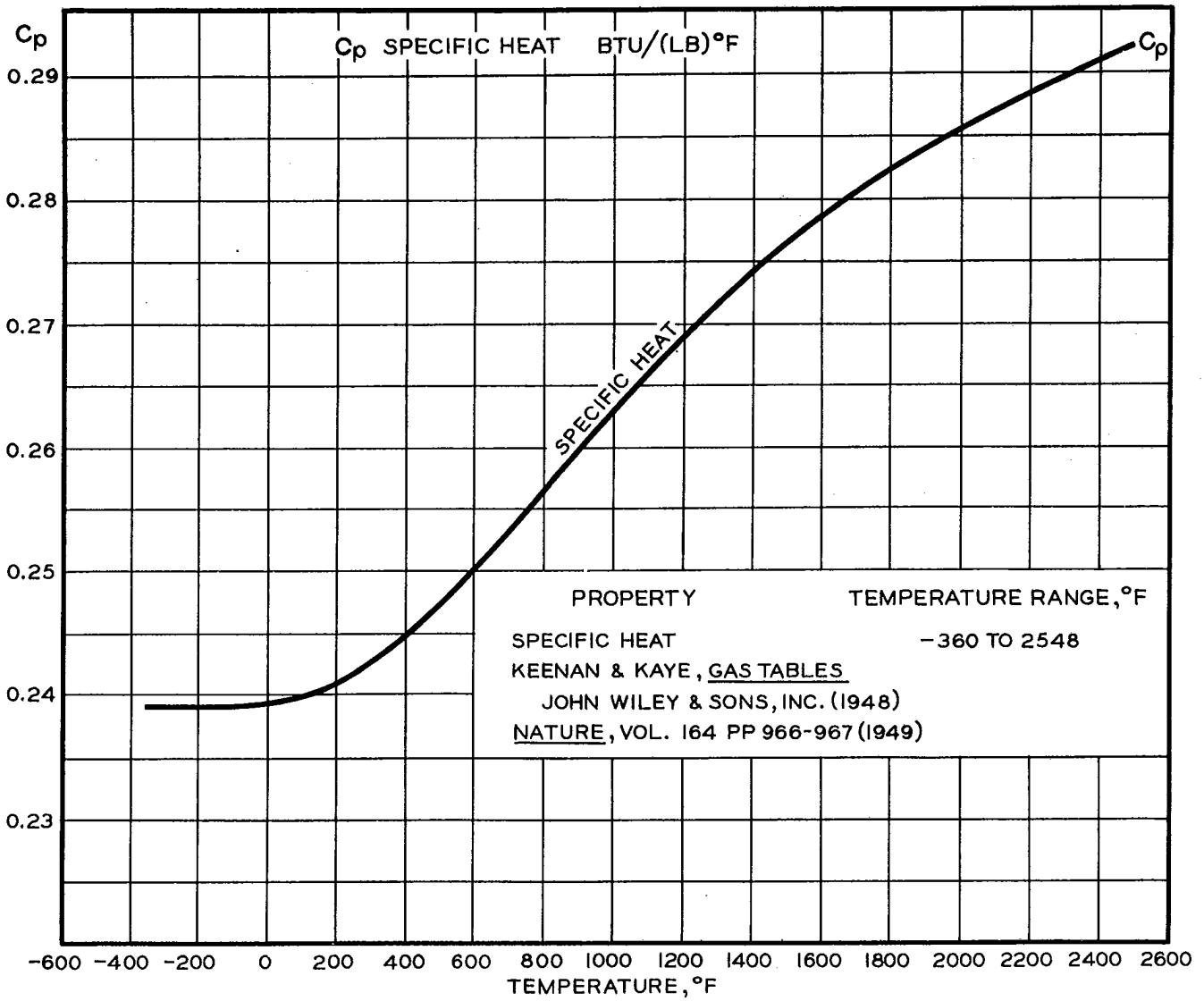


FIG. 3 INSTANTANEOUS SPECIFIC HEAT OF AIR

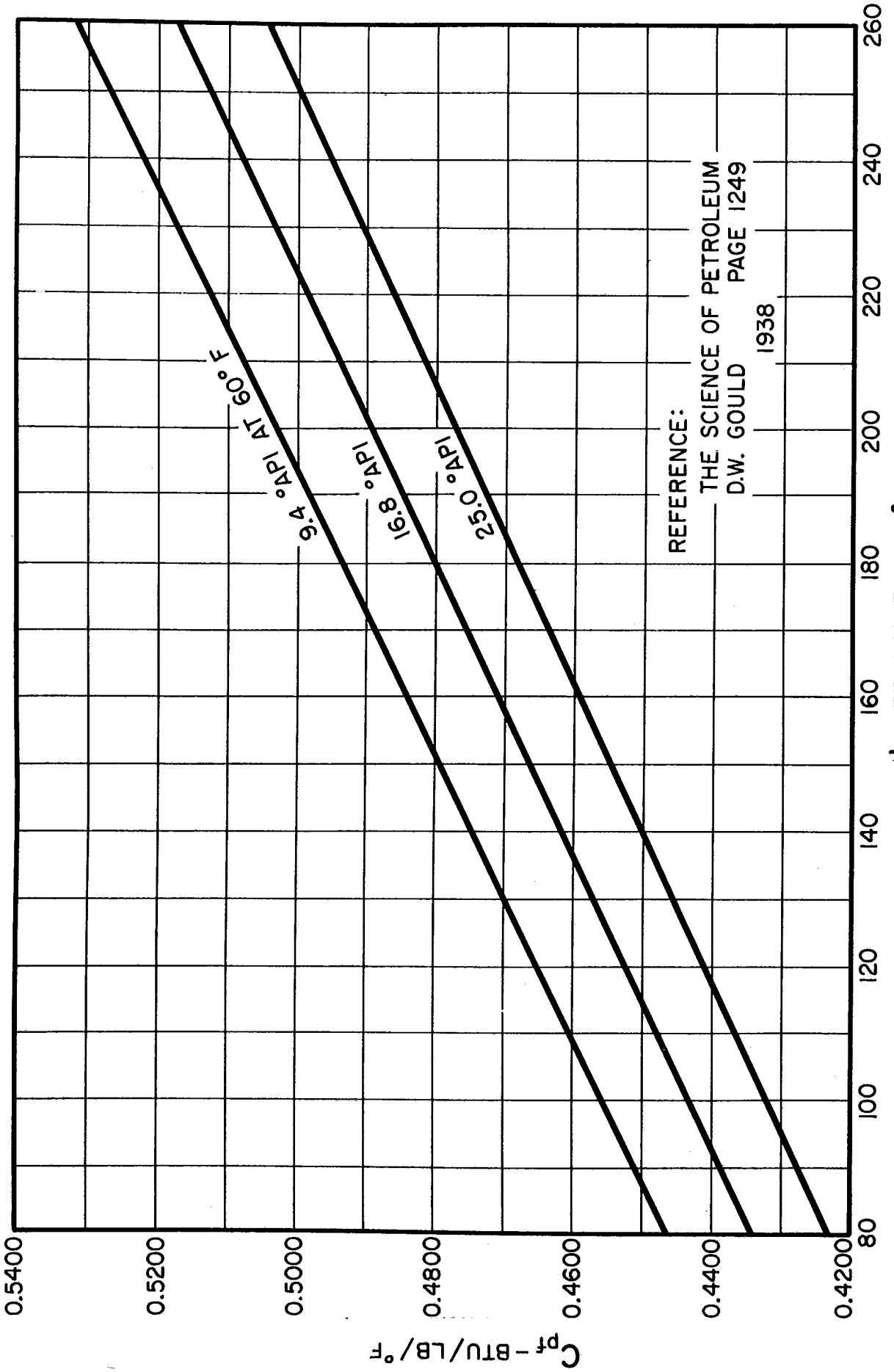


FIG. 4 INSTANTANEOUS SPECIFIC HEAT OF FUEL OIL – 1 ATMOSPHERE

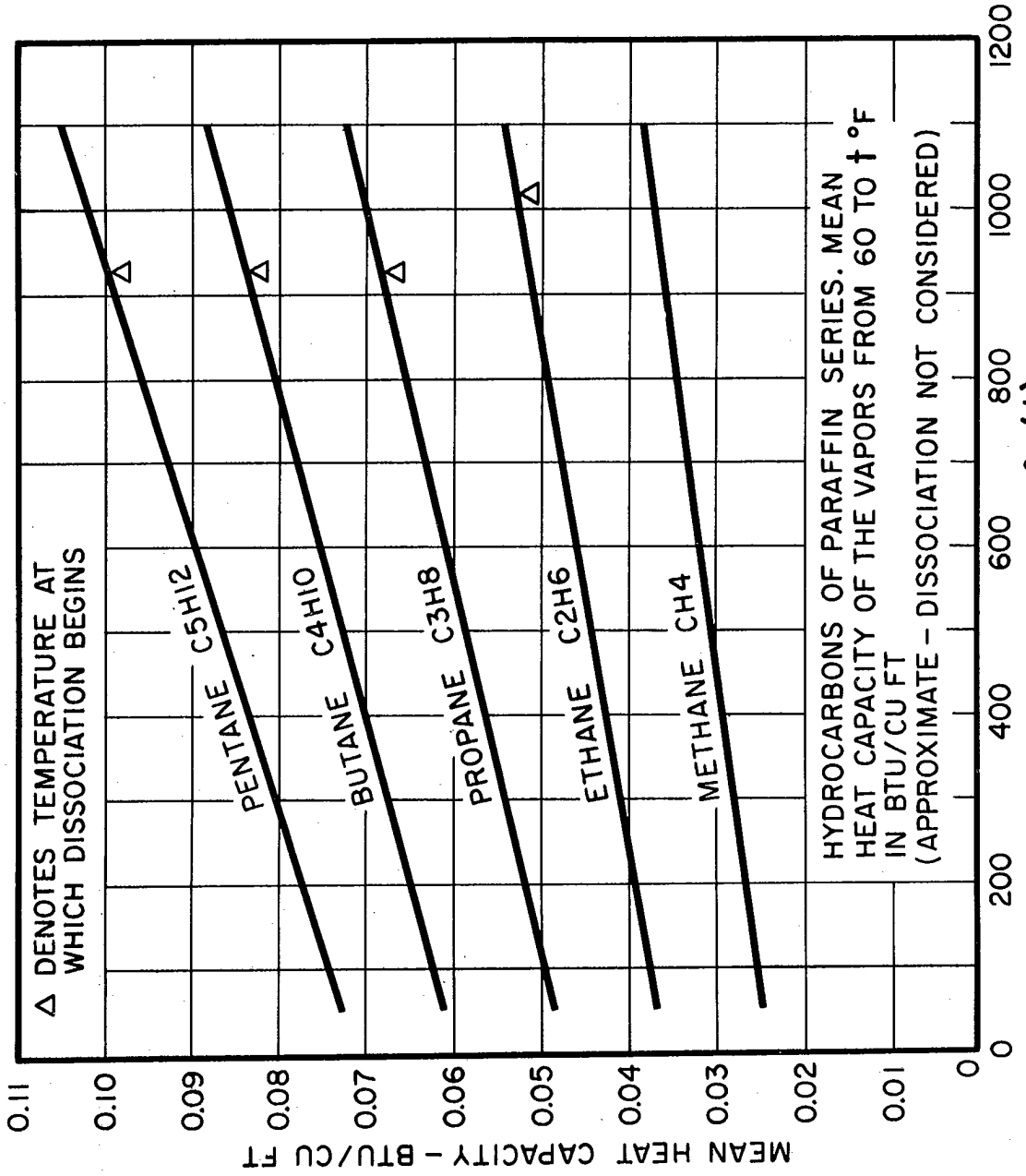


FIG. 5 INSTANTANEOUS SPECIFIC HEAT OF FUEL GAS
(Reference: American Gas Association Publication of 1954, P 124, Edited by Louis Shnidman)

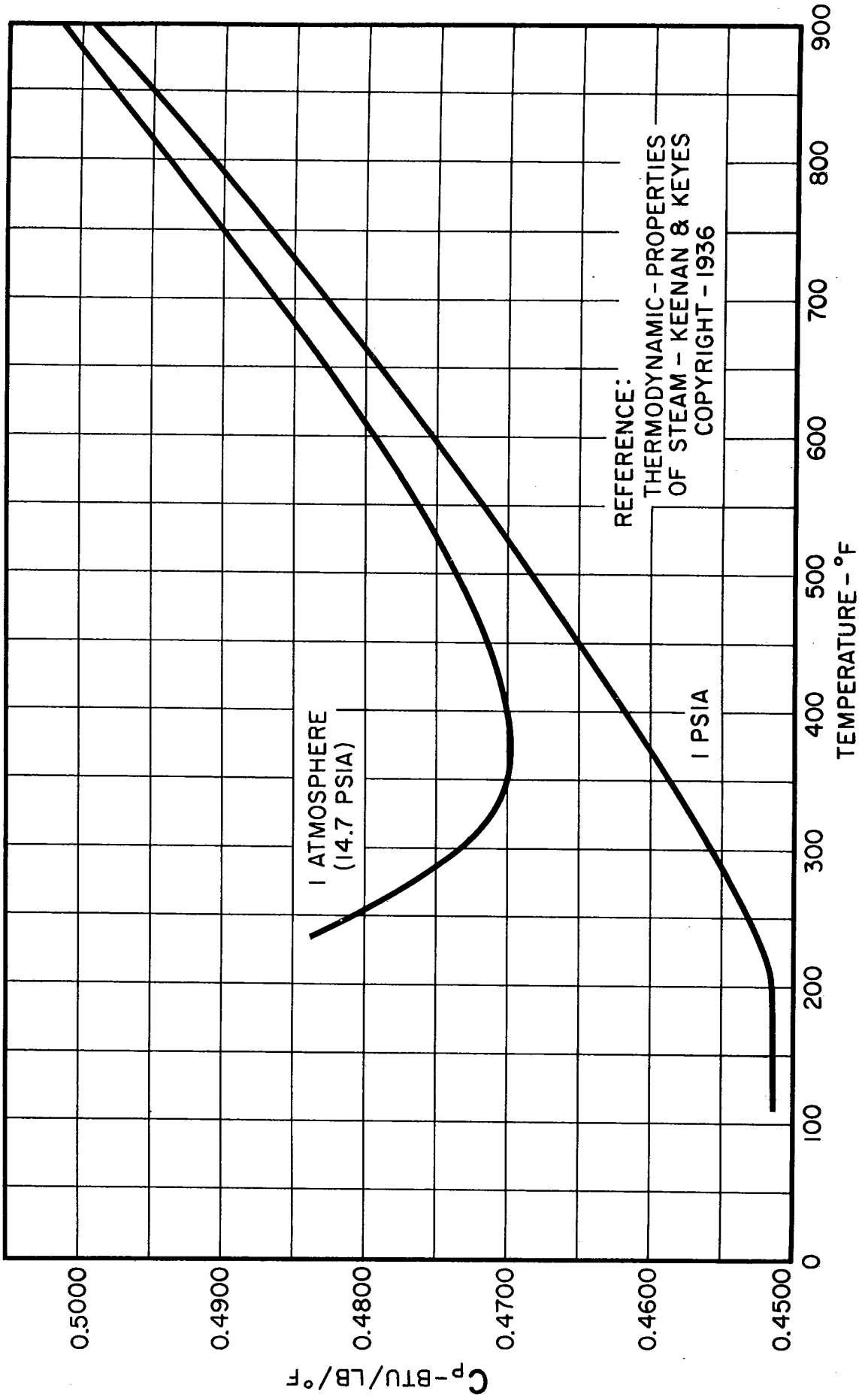


FIG. 6 INSTANTANEOUS SPECIFIC HEAT OF STEAM

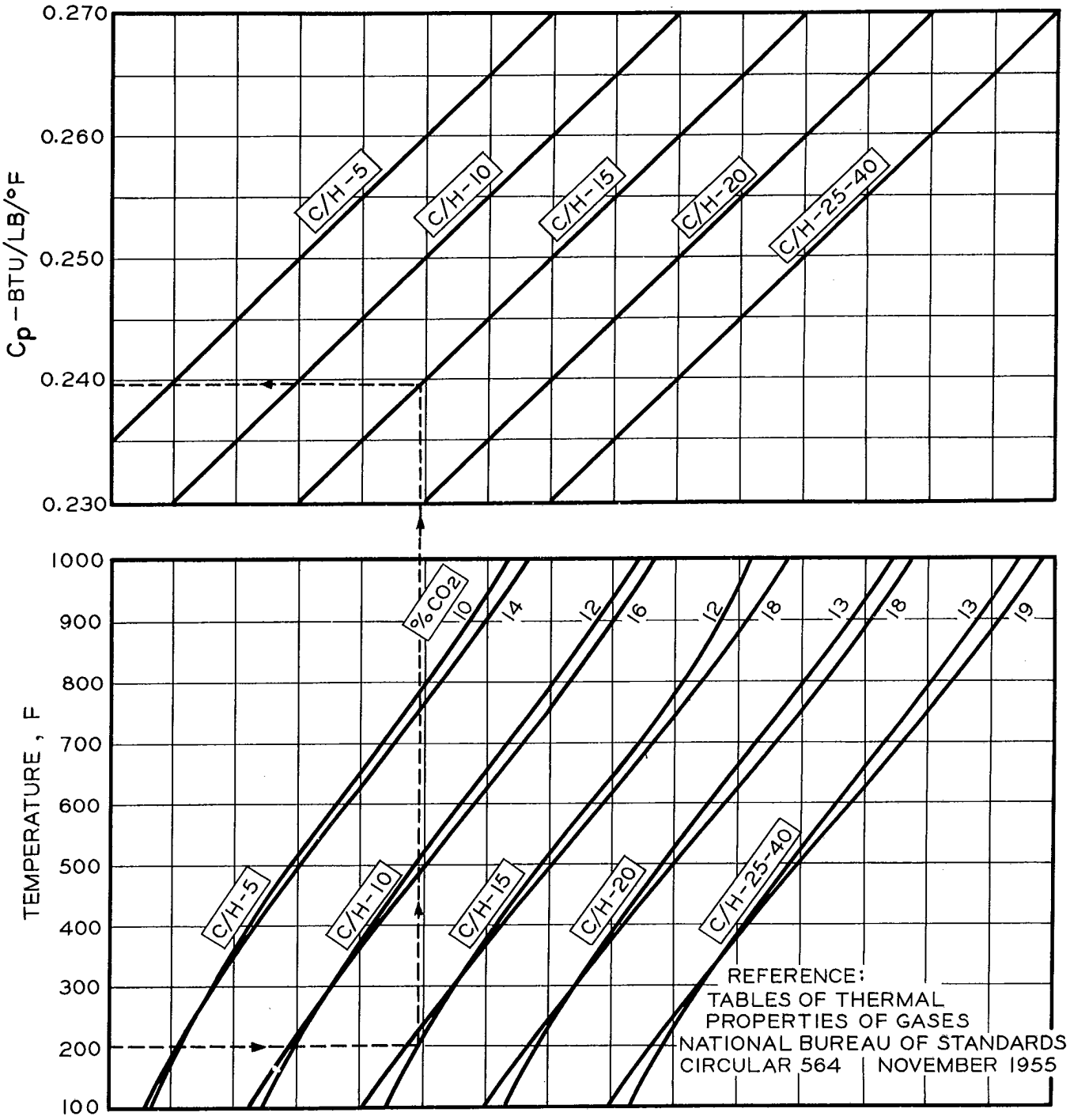


FIG. 7 INSTANTANEOUS SPECIFIC HEAT OF DRY FLUE GAS FOR CARBON HYDROGEN RATIOS (FUEL) = 5 – 40

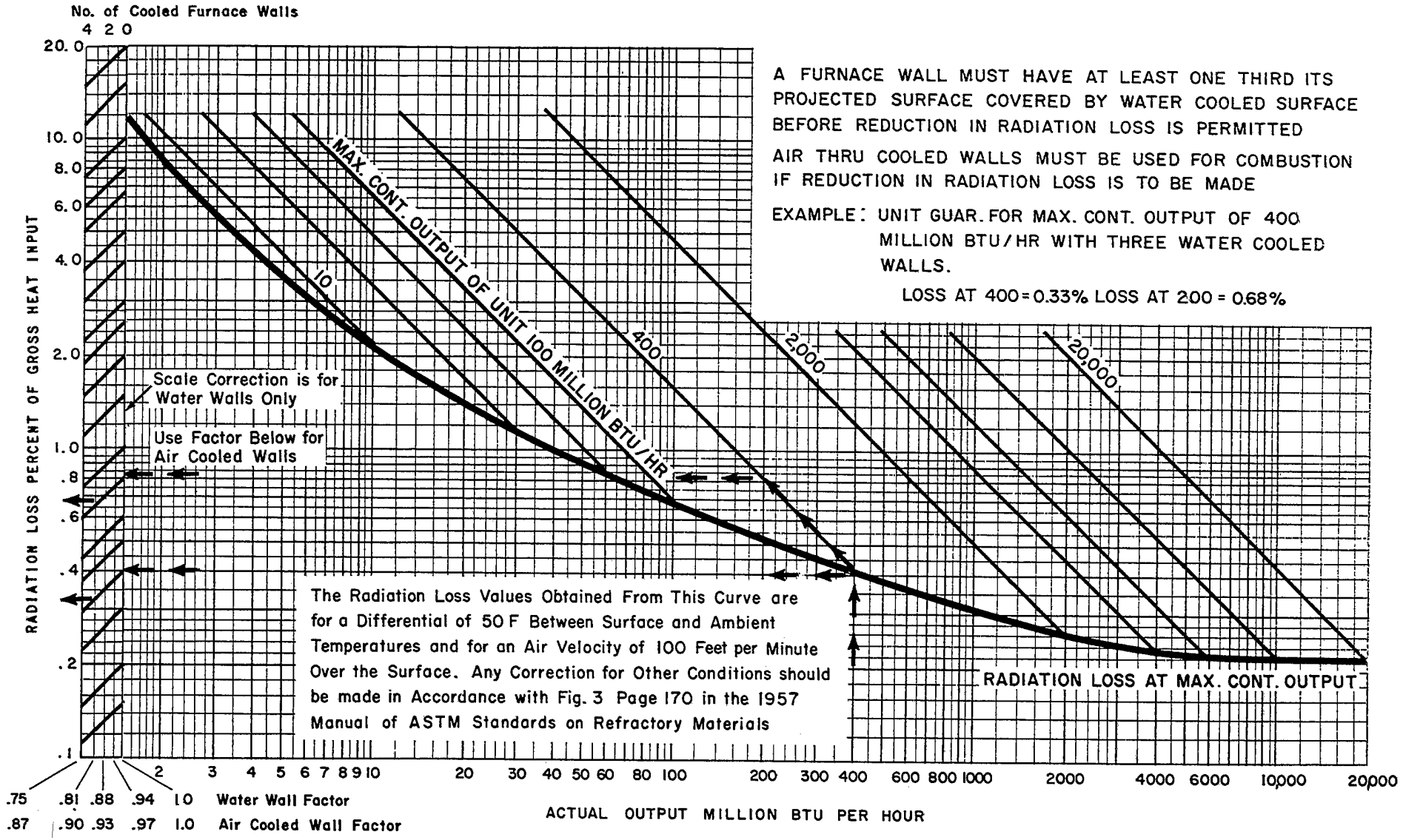


FIG. 8 ABMA STANDARD RADIATION LOSS CHART

To facilitate the use of the major correction which is for air velocity, this correction is included in the Code on Fig. 9, the lower curve of which is the basis of the ABMA curve.

(Published through the courtesy of the American Boiler Manufacturers Association.)

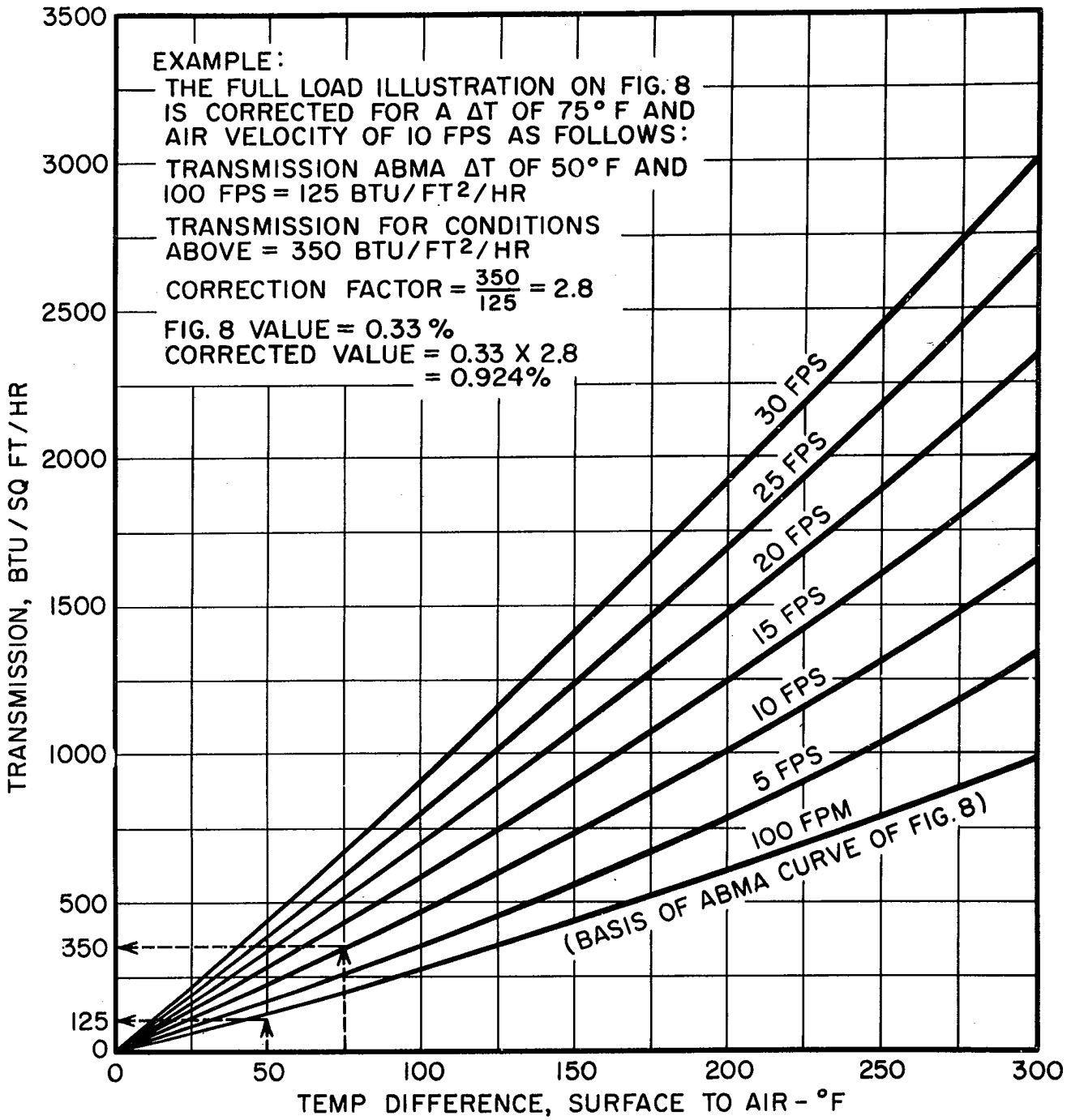


FIG. 9 SURFACE TRANSMISSION FOR VARIOUS AIR VELOCITIES BASED ON EMISSIVITY OF 0.95 AND AIR TEMPERATURE OF 70 F

(Basic data above were obtained from ASTM Standard on Refractory Materials)

SECTION 8, OTHER OPERATING CHARACTERISTICS

8.01 The continuing satisfactory performance of a steam generator requires the determination of many operating characteristics other than its ability to meet its design capacity and efficiency guarantee. This section describes factors affecting performance and how these should be determined by test.

8.02 Measurement of Air Leakage or Infiltration. When it is desired to determine the amount of air infiltration or leakage through any portion of the enclosure of a steam generating unit, beyond the furnace exit, it should be done by comparing excess air, as determined from flue gas analyses. The sampling locations preferably should lie in planes normal to the flue gas flow, located as close as practical to the zones of comparison. Frequency of sampling points should be as recommended in Par. 5.04, "Flue Gas Sampling and Analysis – Sampling Locations." The gas temperatures at the sampling location will determine whether or not a water cooled sampler is required. It is advisable to use a water cooled sampler at temperatures in excess of 950 F.

8.02.1 The amount of air infiltration or leakage is normally expressed in terms of increase in excess air, reduction in CO_2 or per cent leakage. The latter is as follows:

$$W_L \text{ (per cent)} = \frac{(\text{per cent total weight of air at } S_2) - (\text{per cent total weight of air at } S_1)}{(\text{per cent total weight of air at } S_1)} \times 100$$

8.02.2

Where

W_L = Per cent air leakage.

S_1 = Upstream sampling location.

S_2 = Downstream sampling location.

8.02.3 Measurement of air leakage of a regenerative air heater is covered in the Test Code for Air Heaters PTC 4.3.

8.03 Peak Load Capacity. When it is desired to establish the ability of a steam generating unit to maintain anticipated peak load capacity, commercial feedwater or steam flow recording meters may be used. Flows must be corrected to compensate for deviation of test pressures and temperatures at the flow nozzle or orifice, from design pressure and temperature conditions, and the instrument must be calibrated immediately prior to the test.

8.03.1 When desuperheating spray water is to be measured or accounted for as part of capacity determination, and this water flow is not metered, the spray flow rate may be determined by heat balance, using steam flow at either the entrance or exit to the desuperheater, steam pressures and temperatures at the entrance and exit of the desuperheater, and spray water temperature. Temperatures and pressures will be measured as outlined in Par. 4.19, "Steam and Feedwater Temperatures," and Par. 4.21, "Steam and Feedwater Pressures."

8.03.2 Reheat steam flow can be measured or computed as described in Par. 4.17.

8.04 Steam Temperature. When superheater and/or reheater steam temperature characteristic and control ranges thereof are to be verified by test, steam temperature measurement should be in accordance with procedures outlined in Par. 4.19, "Steam and Feedwater Temperatures."

8.04.1 Operating conditions which can affect a temperature test such as steam flow, steam pressure, feedwater temperature, excess air, cold reheat pressure and temperature and characteristics of the fuel fired should be as specified by design. Control apparatus for maintaining and regulating temperature such as burner tilt, recirculating gas fans, spray valves, bypass dampers, etc., shall have been adjusted prior to the test. Selection and setting of burners shall also be agreed upon. The period of operation prior to running such a test should be of sufficient duration to insure stabilization of furnace

cleanliness. All heat transfer surfaces, both internal and external, should be commercially clean (normal operating cleanliness) before starting the test. During the test, only the amount of cleaning shall be permitted as is necessary to maintain normal operating cleanliness.

8.04.2 Measurement of steam flows, temperatures, pressures, and excess air, which provide essential supplementary data, should be as specified in Pars. 4.17, 4.19, 4.21 and 8.02.

8.05 Exit Gas Temperature. When a gas temperature at the exit of a steam generating unit is to be verified by test, the procedures outlined in Par. 5.08, "Flue Gas Temperature," should be followed. Operating conditions, unit cleanliness and necessary test measurements should be given the same consideration as in Par. 8.04.

8.06 Static Pressure of Gas and Air. Static pressure connections shall be installed in a manner as to avoid errors due to gas velocity. Piping or tubing shall preferably be specifically installed for the test, and shall be proved tight with provisions made for cleaning and drainage. The recommendations of I & A Pressure Measurement PTC 19.2, Chapter 6, shall be followed.

8.06.1 Flue gas and air pressures shall be measured by suitable manometers designed, built, installed, calibrated, and used as specified in I & A Pressure Measurement PTC 19.2, Chapter 3, on Liquid -Level Gages.

8.07 Draft Loss, or Resistance to Air or Gas Flow. When a draft loss or resistance across a steam generating unit, or a section of a unit, is to be measured, a differential manometer should be used in preference to absolute draft or pressure gages.

8.07.1 Operating conditions, unit cleanliness and necessary test measurements should be given the same consideration as in Pars. 8.04 and 8.05.

8.08 Pressure Loss. When the steam, water or other fluid pressure loss is to be determined across a steam generating unit, or a portion of a unit, the general pressure measurement procedures specified in Par. 4.21 "Steam and Feedwater Pressures," apply.

8.08.1 In addition to the above measurement technique, either the pressure from all points shall be taken with individual deadweight gages without a manifold or by means of a common manifold with one calibrated Bourdon gage. In the latter case the connections to the manifold shall be double valved. Manometers of suitable range and construction may also be used. Calibrated differential type gages or transducers may be used by agreement.

8.08.2 The steam, water or other fluid flows, pressures and temperatures should be the same as the design conditions for which the pressure loss prediction was made.

8.09 Measurements for Determining Solids. Samples of condensed steam for determination of solids are given in I & A, Methods for the Determination of the Quality and Purity of Steam PTC 19.11. There are three accepted methods for the determination of solids in steam. These are:

(1) Gravimetric method for total solids.
(2) Electrical conductivity method for dissolved solids.
(3) Flame photometry.

8.09.1 The gravimetric determination of total solids in the condensed steam may be made in accordance with Section 3, I & A, Methods for the Determination of the Quality and Purity of Steam PTC 19.11. For measuring performance by the gravimetric method, the results shall be expressed as the average of three determinations made upon a composite sample which shall be taken throughout the entire test period.

8.09.2 The electrical conductivity determination of dissolved solids in the condensed steam shall be made in accordance with Section 4, I & A, Methods for the Determination of the Quality and Purity of Steam PTC 19.11. Remove dissolved gases from the sample as completely as possible by mechanical means without contaminating the sample with any added material which will increase its conductivity. The conductivity shall be corrected to compensate for residual ammonia, carbon dioxide or other gases

remaining in the sample and the dissolved solids shall be calculated from this corrected conductivity. For measuring performance by the electrical conductivity method, the average of ten determinations made at regular intervals throughout the test period shall be used.

8.09.3 Where extreme purities are encountered use the trace element method, Method B, in accordance with ASTM D 1428 "Sodium and Potassium in Industrial Water and Water Formed Deposits by Flame Photometry."

SECTION 9, APPENDIX

9.1 Derivation of the Weight of Dry Air. The following is the derivation of the equation for computing the weight of dry air per pound of "as fired" fuel. See Par. 7.2.8.1. In this derivation the assumption is made that whatever sulfur is present in the fuel is burned to sulfur dioxide. This is not entirely true, a fraction may be burned to sulfur trioxide and another fraction could form oxides with the ash. In addition some of the sulfur may be in the form of sulfides or sulfates and unavailable for combustion. However, the treatment presented here appears to be the best for general usage. An additional minor assumption made is that all the sulfur dioxide sampled is removed in the orsat by the carbon dioxide reagent.

$$\text{Pounds of dry gas per mole of dry gas} = 44.01\frac{(CO_2)}{100} + 28.01\frac{(CO)}{100} + 32.00\frac{(O_2)}{100} + 28.02\frac{(N_2)}{100}$$

$$\text{Pounds of equivalent carbon burned per mole of dry gas} = 12.01\frac{(CO_2 + CO)}{100}$$

In order to use this equation the pounds of carbon burned per pound of "as fired" fuel must be adjusted for the sulfur dioxide absorbed in the orsat as carbon dioxide.
To reduce the sulfur in the fuel to its carbon equivalent, multiply the sulfur in the fuel by $\left[\frac{12.01}{32.07}\right]$

Molecular weight: C = 12.01
S = 32.07

Then the equivalent carbon burned is $C_b + \frac{12.01}{32.07}S$

The pounds of dry gas per pound of "as fired" fuel is obtained as follows:

$$W_{G'} = \frac{\text{lb dry gas}}{\text{mole dry gas}} \times \frac{1}{\frac{\text{lb carbon}}{\text{mole dry gas}}} \times \frac{\text{lb carbon}}{\text{lb A.F. fuel}} = \frac{\text{lb dry gas}}{\text{lb A.F. fuel}}$$

$$W_{G'} = \frac{44.01\,(CO_2) + 28.01\,(CO) + 32.00\,(O_2) + 28.02\,(N_2)}{12.01(CO_2 + CO)}\left(C_b + \frac{12.01}{32.07}S\right)$$

$$\text{Pounds of nitrogen per mole of dry gas} = 28.02\frac{(N_2)}{100}$$

$$W_{NG'} = \frac{1}{\frac{\text{lb dry gas}}{\text{mole dry gas}}} \times \frac{\text{lb nitrogen}}{\text{mole dry gas}} = \text{pounds of nitrogen in the dry gas per pound of dry gas}$$

$$W_{NG'} = \frac{28.02\,(N_2)}{44.01\,(CO_2) + 28.01\,(CO) + 32.00\,(O_2) + 28.02\,(N_2)}$$

Pounds of nitrogen in the dry gas per pound of dry gas multiplied by pounds of dry gas per pound of "as fired" fuel = $W_{NG'} \times W_{G'}$ = Pounds of nitrogen in the dry gas per pound of "as fired" fuel = $W_{G'N_2}$.

Therefore:

$$W_{G'N_2} = \frac{28.02\,(N_2)}{44.01\,(CO_2) + 28.01\,(CO) + 32.00\,(O_2) + 28.02\,(N_2)} \times \frac{44.01\,(CO_2) + 28.01\,(CO) + 32.00\,(O_2) + 28.02\,(N_2)}{12.01\,(CO_2 + CO)}\left(C_b + \frac{12.01}{32.07}S\right)$$

$$W_{G'N_2} = \frac{28.02\,(N_2)}{12.01\,(CO_2 + CO)}\left(C_b + \frac{12.01}{32.07}S\right)$$

$W_{A'}$ = lb of dry air per lb of "as fired" fuel

N = lb of nitrogen per lb of "as fired" fuel – (From laboratory analysis of the fuel)

$W_{A'} = \dfrac{W_{G'N_2} - N}{0.7685}$ = weight of dry air per pound of "as fired" fuel.

0.7685 = the pounds of nitrogen per pound of standard air (see International Critical Tables – Vol. 1)

The complete equation for the weight of dry air per pound of "as fired" fuel is equal to:

$$W_{A'} = \frac{28.02\,(N_2) \times \left(C_b + \dfrac{12.01}{32.07}\,S\right)}{\dfrac{12.01\,(CO_2 + CO)}{0.7685}} - N$$

9.2 Computation of Theoretical and Excess Air. For those interested in calculating theoretical and excess air the following formulas are useful:

Theoretical Air:

$$A'_\theta = 11.51\,C + 34.30\left(H - \frac{O}{7.937}\right) + 4.335\,S$$

$A'_\theta = \dfrac{\text{lb of dry air}}{\text{lb A.F. fuel}}$ = Theoretical dry air in pounds required to completely burn a pound of "as fired" fuel

C = $\dfrac{\text{lb carbon}}{\text{lb A.F. fuel}}$ From laboratory analysis of the fuel

H = $\dfrac{\text{lb hydrogen}}{\text{lb A.F. fuel}}$ From laboratory analysis of the fuel

O = $\dfrac{\text{lb oxygen}}{\text{lb A.F. fuel}}$ From laboratory analysis of the fuel

S = $\dfrac{\text{lb sulfur}}{\text{lb A.F. fuel}}$ From laboratory analysis of the fuel

All constants are based on molecular weights from National Bureau of Standards Circular 564 dated 11/1/55.

Excess air:

$$A'_X = \frac{W_{A'} - A'_\theta}{A'_\theta} \times 100$$

A'_X = per cent excess air

$W_{A'} = \dfrac{\text{lb of dry air}}{\text{lb A.F. fuel}}$ = Weight of dry air per pound of "as fired" fuel

$A'_\theta = \dfrac{\text{lb of dry air}}{\text{lb A.F. fuel}}$ = Pounds of dry air theoretically required to completely burn a pound of "as fired" fuel

9.3 Derivation of Flue Gas Specific Weight. The following derivation of flue gas specific weight at 68 F and 14.7 psia (see Par. 7.3.2.08) is based on the assumption that the flue gas conforms to the ideal gas law:

$$PV = \Psi R_u T$$

Where

P = $\frac{\text{lb}}{\text{sq ft}}$ = Absolute pressure

V = cu ft = volume

Ψ = number of pound moles

R_u = $\frac{1545 \text{ ft-lb}}{\text{lb mole, deg R}}$ = Universal gas constant (see International Critical Tables, Vol. 1, page 18)

T = deg R = Temperature Rankine

Multiplying both sides by the molecular weight M

$$\therefore MPV = M\Psi M R_u T$$

But $M\Psi = \mathbb{W}$ = Pounds of gas

$$MPV = \mathbb{W} R_u T$$

$$MP = \frac{\mathbb{W}}{V} R_u T$$

Specific weight of gas = $\gamma = \frac{\mathbb{W}}{V}$

$$\therefore MP = \gamma R_u T$$

$$\gamma = \frac{P}{T} \times \frac{M}{R_u}$$

At standard conditions:

$$P = 14.7 \text{ lb per sq in.} \times 144 \frac{\text{sq in.}}{\text{sq ft}} = 2115 \frac{\text{lb}}{\text{sq ft}}$$

$$T = 68 \text{ F} + 460 = 528 \text{ R}$$

$$\frac{P}{T} = \frac{2115}{528} = 4.01$$

Therefore:

$$\gamma = 4.01 \frac{M}{R_u}$$

$$\gamma = \frac{4.01}{100} \left[\frac{(CO_2 \times M_{CO_2}) + (O_2 \times M_{O_2}) + (N_2 \times M_{N_2}) + (CO \times M_{CO}) + (SO_2 \times M_{SO_2}) + (H_2 \times M_{H_2}) + (HC \times M_{HC})}{1545} \right]$$

$$\gamma = 0.0401 \left[\frac{CO_2}{\frac{1545}{44.01}} + \frac{O_2}{\frac{1545}{32.00}} + \frac{N_2}{\frac{1545}{28.02}} + \frac{CO}{\frac{1545}{28.01}} + \frac{SO_2}{\frac{1545}{64.07}} + \frac{H_2}{\frac{1545}{2.016}} + \frac{HC}{\frac{1545}{M_{HC}}} \right]$$

This simplifies to the equation for the flue gas specific weight given in Par. 7.3.2.08 and below.

$$\gamma = 0.0401 \left[\frac{CO_2}{35.11} + \frac{O_2}{48.28} + \frac{N_2}{55.14} + \frac{CO}{55.16} + \frac{SO_2}{24.12} + \frac{H_2}{766.36} + \frac{HC}{\frac{1545}{M_{HC}}} \right]$$

9.4 Heating Value of Carbon As It Occurs In Refuse. A review of the published information on the heat value of carbon to be used in estimating the heat loss due to combustible in the refuse in boiler heat balance reveals a variation ranging approximately from 14,400 to 14,600 Btu per pound mainly due to the form in which the carbon is present. See supplementary volume to Chemistry of Coal Utilization.

The Code Committee has used the value of 14,500 on the basis that its accuracy is consistent within other aspects of the Code and with the endorsement of the Chairman of PTC 3.2 after his referral of the matter to the U.S. Bureau of Mines.

9.5 Radiation and Convection Loss. This is the only significant loss in the Code, the computation of which is not based on test measurements. The Committee in its early considerations of this subject were desirous to treat the loss like all others, i.e. to take test readings and compute the loss. However, the test installation required was so extensive that in the opinion of the Committee, it was an unwarranted requisite. It was, therefore, decided to estimate this loss using the ABMA curve as was done in the 1946 Edition of the Code. The Manufacturers revised this curve based on their joint availability of data, and extended it well beyond present day capacities, see Fig. 8. The curve's values were checked against the actual measured losses on several large boilers and the curve values found to be conservatively high.

9.5.1 In order that this curve may be improved in accuracy in future years, users of this Code are encouraged to take radiation and convection loss readings on acceptance tests and from these compute the loss and report the results to the ASME Power Test Code Committee No. 4 on Steam Generating Units, giving a detailed description of the unit in regard to exposure, wind velocities, type of wall construction, method of testing, etc. In conducting such tests the following method is suggested for obtaining test data and computing the loss.

9.5.2 Determine this loss through the steam generator walls, roof, bottom, air heater, ducts, piping and any other exposed surfaces by installing at the center of every one hundred square feet of area a pair of thermocouples in a block of insulation of known conductivity. With the temperature gradient measured by the thermocouples, the known distance between thermocouples and the conductivity of the insulation compute the radiation and conductivity loss for each 100 square feet. The sum of these losses for each 100 square feet divided by the steam generator heat input rate will be the radiation and convection loss for the unit.

9.6 Conversion of Heating Value from Constant Volume to Constant Pressure. The formula for the conversion of the high-heat value at constant volume as obtained with the bomb calorimeter to the high-heat value at constant pressure is based on the first law of thermodynamics and the general energy equations. In a heating value determination there is no thermodynamic work performed nor kinetic energy change, therefore, the heating value at constant volume is the change in internal energy between the reactants and products. Similarly and for the same reasons, the heating value at constant pressure is the change in enthalpy between the reactants and products. This being the situation the general energy equation relating the constant volume heating value with the constant pressure heating value is as follows:

$$H_{fp} = H_{fv} + \frac{\Delta P V}{778.2}$$

Assuming the perfect gas law can be applied to the gaseous constituents of the reactions:

$$\frac{\Delta P V}{778.2} = \frac{\Delta \Psi R_u T}{778.2}$$

and

$$H_{fp} = H_{fv} + \frac{\Delta \Psi R_u T}{778.2}$$

where

$H_{fp} = \frac{\text{Btu}}{\text{lb A.F. fuel}}$ = High-heat value of fuel at constant pressure

$H_{fv} = \frac{\text{Btu}}{\text{lb A.F. fuel}}$ = High-heat value of fuel at constant volume

$\Delta\Psi$ = Change in the number of pound moles of gaseous products when compared to the pound moles of gaseous reactants. Only the number of gaseous moles are of importance because the volume occupied by a mole of liquid or solid material is so small that it is insignificant and the perfect gas law does not apply to these fractions.

$R_u = \frac{1545 \text{ ft-lb}}{\text{lb mole R}}$ = Universal Gas Constant

T = 537 R This is the absolute value of the standard calorimeter temperature

778.2 ft-lb = 1 Btu = mechanical equivalent of heat.

Determination of the change in the number of moles caused by the combustion reactions of solid or liquid fuels.

REACTANTS		PRODUCTS
C (solid) or (liquid)	+ O_2 (gas)	CO_2 (gas)
N (solid) or (liquid)		N_2 (gas)
H (solid) or (liquid)	+ ½ O_2 (gas)	H_2O (liquid)
S (solid) or (liquid)	+ O (Gas)	SO_2 (gas)

O, A, M — in combined state as reactants, therefore, they cannot enter reaction except for occasional rare constituents.

The carbon (C) reaction has no change in the number of gaseous moles from reactants to products, therefore, no correction required.

The Nitrogen (N) reaction, assuming it is released as a gas in the products and reacted as a solid or liquid, increases by one (1) mole per mole of nitrogen reactant. This causes a PV change and requires an adjustment between the high-heat value at constant pressure and volume.

Hydrogen as a liquid or solid portion of a compound is released and unites with oxygen to form water which is condensed to a liquid. Therefore, the net effect of the reaction is a decrease of half a mole of product for each mole of hydrogen exclusive of that in the fuel moisture.

Solid sulfur reacts with a mole of oxygen to form a mole of sulfur dioxide in the products. There is no net change in gaseous constituents, therefore, no correction required.

All oxygen in the fuel is assumed to be in the combined state. The compounds envisioned are water and metallic oxides in the ash. In the foregoing forms the oxygen in the fuel will not react and appears unchanged in the products and no correction is required. Similar reasoning applied to the ash and moisture in the fuel proves no need for a correction on their behalf.

$$\Delta\Psi = \frac{-N}{28.016} + \frac{1}{2}\,\frac{H}{2.016}$$

Note the sign convention — Where there is an increase in the mole volume, work is done on the surroundings and results in a negative sign.

$N = \frac{\text{lb}}{\text{lb A. F. fuel}}$ = Pounds of nitrogen per pound of "as fired" fuel

$28.016 = \frac{\text{lb}}{\text{lb mole}}$ = Pounds of nitrogen per pound mole of nitrogen

$H = \frac{\text{lb}}{\text{lb A. F. fuel}}$ = Pounds of hydrogen exclusive of that in the moisture per pound of "as fired" fuel

$2.016 = \frac{\text{lb}}{\text{lb mole}}$ = Pounds of hydrogen per pound mole of hydrogen.

Substituting into the general equation:

$$H_{fp} = H_{fv} + \left(\frac{-N}{28.016} + \frac{H}{4.032}\right) \frac{R_u T}{778.2}$$

Substituting for R_u and assuming a standard calorimeter temperature of 77 F this reduces to:

$$H_{fp} = H_{fv} + \left(\frac{-N}{28.016} + \frac{H}{4.032}\right) 1066$$

The nitrogen in liquid and solid fuel is less than 2 per cent by weight, therefore, the nitrogen correction is less than 0.76 Btu per pound of fuel. This correction is only required if the nitrogen is in the solid or liquid form in the fuel and is released as a gas during combustion. If it is an entrapped gas initially or forms an ash compound during combustion, no correction is required. In considering these various contingencies it was decided to neglect the nitrogen correction and the formula as found in Par. 7.2.6.2 and given here reduces to the following results:

$$H_{fp} = H_{fv} + 264.4\,H$$

9.7 References. The following material may be helpful to the Code user who may wish to investigate in more details various facets of the Code.

(1) Combustion Calculations for Multiple Fuels, by Tibor Buna, Trans. ASME, Vol. 78, August, 1956.
(2) Code Testing of Large Boilers – Input-Output or Heat-Loss Method by J. A. Bostic and W. F. Long, Paper No. 60 – Power – 5, not published in Trans. ASME or Mechanical Engineering, on file in Engineering Societies Library.
(3) Efficiency Determination of Marine Boilers: Input-Output Versus Heat-Loss Method, by L. Cohen and W. A. Fritz, Jr., ASME Journal of Engineering for Power, Vol. 84, January, 1962.
(4) Performance Testing of Large Steam Generators, by R. E. Vuia, Paper No. 62-WA-267, not published in Trans. ASME or Mechanical Engineering, on file in Engineering Societies Library.

1968 ADDENDUM
STATIONARY STEAM GENERATING UNITS, PTC 4.1–1964
Date of Issue, September, 1968

PTC 4.1 Stationary Steam-Generating Units has revised Paragraphs 0.6 and 1.05.

The orginal wording and revised wording of these two paragraphs follow.

Original wording:

0.6 The general instructions contained in this Code shall also apply to the testing of high temperature water heaters, except that efficiency determination shall be by heat loss method only, as described in Section 5. The input-output method is not acceptable because of potentially large inaccuracies introduced by the presence of indeterminant quantities of steam in the output and by the small temperature measurement errors in a large volume flow output.

Test capacity or output shall be determined from measured heat input and efficiency, or by direct measurement of heat output if a high degree of accuracy is not required.

1.05 Capacity of steam generators is defined as actual evaporation in pounds of steam per hour delivered or Btu per hour absorbed by the working fluid or fluids. Capacity of hot water heaters is defined as the heat absorbed by water and the heat of any steam that may be generated (Btu per hour).

Revised wording:

0.6 The general instructions contained in this Code shall also apply to the testing of high temperature water heaters. When either the heat loss or input-output method of testing (see Par. 1.04) is used, the unit must be pressurized above saturation temperature to assure against the presence of steam at the point of measurement. The amount of pressurization shall be an item of agreement. When the input-output method (see Par. 1.04) is used to test such equipment, the water temperature rise through the unit shall be determined by differential temperature measurements rather than by separate measurements of inlet and outlet water temperatures (see Pars. 31, 32, and 44, Chapter 4, PTC-19.3, Part 3, 1961).

When using the heat loss method to determine efficiency, the capacity or output point at which the run is being made shall be determined from measured heat input and efficiency (see Par. 4.02) or by direct measurement of heat output (see Pars. 4.14, 4.15, and 4.16).

1.05 Capacity of steam generators is defined as actual evaporation in pounds of steam per hour delivered or Btu per hour absorbed by the working fluid or fluids. Capacity of hot water heaters is defined as the heat absorbed by the water (Btu per hour).

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345 East 47th Street, New York, N. Y. 10017
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1969 ADDENDUM
STATIONARY STEAM GENERATING UNITS, PTC 4.1–1964

Date of Issue, March, 1969

PTC Committee 4.1 Stationary Steam-Generating Units has revised Paragraphs 3.05.2, 3.05.3 and 7.5.4.

The original wording and revised wording of these three paragraphs follow.

Original wording:

3.05.2 Before the test is started, it shall be determined whether the fuel to be fired is substantially as intended.

3.05.3 Any departures from standard or previously specified conditions in physical state of equipment, cleanliness of heating surfaces, fuel characteristics, or constancy of load, shall be described clearly in the report of the test.

Revised wording:

3.05.2 Before the test is started, it shall be determined whether the fuel to be fired is substantially as intended. The obtaining of a reliable, accurate efficiency test for the purpose of equipment acceptance is dependent upon the fuel being in close agreement with the fuel for which the steam generating unit was designed. Significant deviations of fuel constituents and high heating value can result in appreciable inaccuracies in heat loss calculations and resulting efficiencies. The magnitude of deviation that is tolerable is difficult to establish, but it should be recognized that fuel analysis variation producing changes in high heating value in the order of 10% can alter final calculated efficiency in the order of 1%.

3.05.3 Any departures from standard or previously specified conditions in physical state of equipment, cleanliness of heating surfaces, fuel characteristics, or constancy of load, shall be described clearly in the report of the test. If deviations of operating conditions or fuel characteristics do occur, appropriate adjustments to calculated results shall be applied in accordance with provisions in Section 7 for Corrections to Standard or Guarantee Conditions, recognizing that this will not produce the precise results to be obtained by testing with a fuel that would not require such calculation adjustments.

Original wording:

7.5.4 Corrections to the heat losses, "Heat loss due to moisture in fuel" and "Heat loss due to hydrogen in fuel" for changes of moisture and hydrogen content from the test fuel to the fuel used for the standard or guaranteed computations, are made by substituting the weight of moisture or hydrogen per pound of fuel in the standard or guaranteed fuel for the weight of moisture or hydrogen per pound of fuel, of the test fuel, in the heat loss formulas.

Revised wording:

7.5.4 Corrections to heat losses; dry gas loss, loss due to moisture in the fuel, loss due to hydrogen in the fuel, are made by substituting in all formulae (Items 24, 25, 65, 66, 67 of Abbreviated Efficiency Test Form) affecting the calculation of these losses, the design values of fuel constituents and design high heating value of the fuel, but using test gas temperatures, test reference temperature and test unburned combustible in refuse, where applicable and when appropriately adjusted as specified in paragraphs 7.5.2 and 7.5.3.

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